Lepton flavor of four-fermion operator and fermion portal dark matter

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Yuxuan He, GL, Jia Liu, Xiao-Ping Wang, Xiang Zhao, 2407.06523

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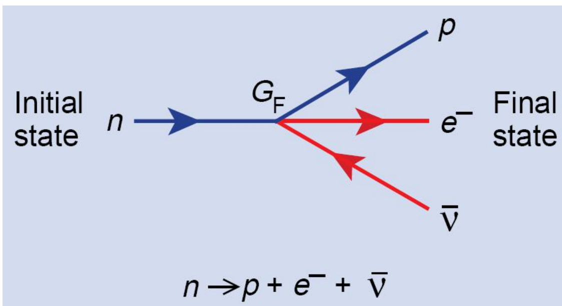
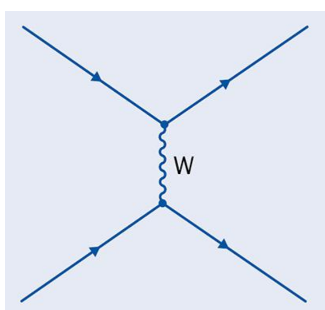
Four-fermion operators

Four-fermion interaction prior to the SM



$q^2 \ll M_W^2$



Historical Fermi theory

$$\mathscr{L} = -\frac{4G_F}{\sqrt{2}} \left(\bar{\psi}_i \gamma_\mu P_L \psi_j\right) \left(\bar{\psi}_l \gamma^\mu P_L \psi_k\right)$$

Weak interaction

$$\frac{4G_F}{\sqrt{2}} = \frac{g^2}{2M_W^2}$$

“new physics” scale is determined

$$\Lambda \sim M_W$$

Four-fermion operators

Four-fermion interactions in the SMEFT ($d = 6$) Wilson coefficients $\frac{C_i}{\Lambda^2}$

unknown C_i and Λ

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu} u_t)$		

B. Grzadkowski, et al, 1008.4884 (JHEP)

Four-fermion operators

Flavor symmetry

Class	Operators	No symmetry: 3 Gen.		No symmetry: 1 Gen.		$U(3)^5$: Exact		$U(3)^5$: $\mathcal{O}(Y^1_{e,d,u})$		$U(3)^5$: $\mathcal{O}(Y^1_e, Y^1_d Y^2_u)$	
	$(\bar{L}L)(\bar{L}L)$	171	126	5	–	8	–	8	–	14	–
	$(\bar{R}R)(\bar{R}R)$	255	195	7	–	9	–	9	–	14	–
8	$(\bar{L}L)(\bar{R}R)$	360	288	8	–	8	–	8	–	18	–
	$(\bar{L}R)(\bar{R}L)$	81	81	1	1	–	–	–	–	–	–
	$(\bar{L}R)(\bar{L}R)$	324	324	4	4	–	–	–	–	4	4

CP-even -odd

strongly suppressed

Faroughy, Isidori, Wilsch, Yamamoto 2005.05366 (JHEP)

Focus on the semileptonic operator of type $\overline{L}R\overline{R}L$

$$O^{\alpha\beta st}_{ledq} = (\bar{L}^j_\alpha e_{R\beta})\left(\bar{d}_{Rs} Q^j_t\right) \qquad L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \qquad Q = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$$

flavor indices: $s = t = 1$

$(\alpha, \beta) = (2,2)\,,(1,2)$

Semileptonic four-fermion operator

Lepton flavor conserving (LFC) scenario

observables

Operators		L	EW	C
$(\bar{L}R)(\bar{R}L)$ + h.c.				
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$	✓	✗	✓

- L: low-energy charged current processes (neutron, nuclear, and meson decays)
- EW: electroweak precision observables
- C: Drell-Yan collider processes ($pp \to ll$ and $pp \to l\nu$)

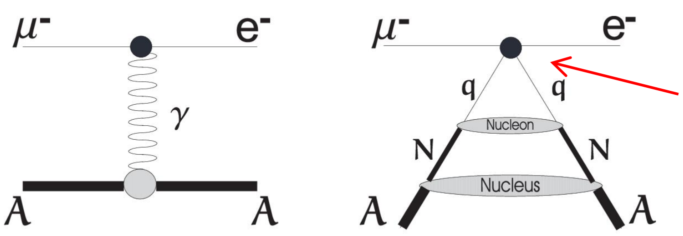
In order to avoid tensions among different observables, global fits are essential. Using current data,

$$C_{ledq}^{2211}/\Lambda^2 = (0.017 \pm 0.039)\ \mathrm{TeV}^{-2}$$ **V. Cirigliano, et al., 2311.00021 (JHEP)**

consistent with zero at 1 sigma

Semileptonic four-fermion operator

Lepton flavor violating (LFV) scenario



probe of the LFV semileptonic operator

$$\mathrm{CR}\left(\mu^{-}+(A, Z) \rightarrow e^{-}+(A, Z)\right) \equiv \frac{\Gamma\left(\mu^{-}+(A, Z) \rightarrow e^{-}+(A, Z)\right)}{\Gamma\left(\mu^{-}+(A, Z) \rightarrow \text { capture }\right)}$$

	cLFV obs.	Present upper bounds (90% CL)	
	$\mathrm{CR}(\mu \to e, \mathrm{S})$	7.0×10^{-11}	Badertscher *et al.* (1982)
	$\mathrm{CR}(\mu \to e, \mathrm{Ti})$	4.3×10^{-12}	SINDRUM II (1993)
	$\mathrm{CR}(\mu \to e, \mathrm{Pb})$	4.6×10^{-11}	SINDRUM II (1996)
✔	$\mathrm{CR}(\mu \to e, \mathrm{Au})$	7.0×10^{-13}	SINDRUM II (2006)

Semileptonic four-fermion operator

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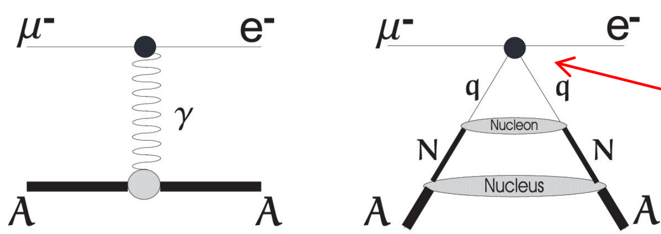

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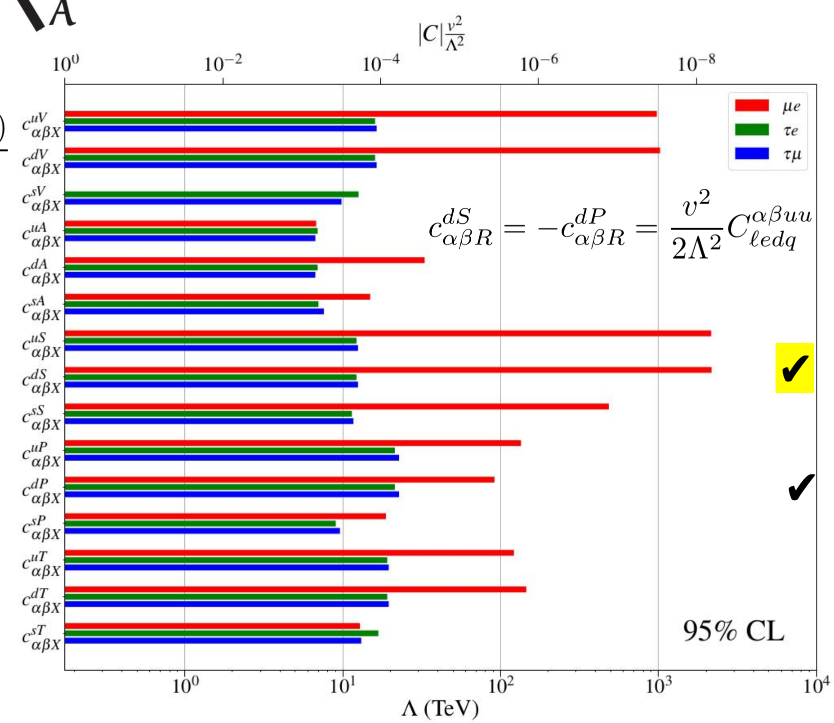


one-at-a-time

Current constraint:

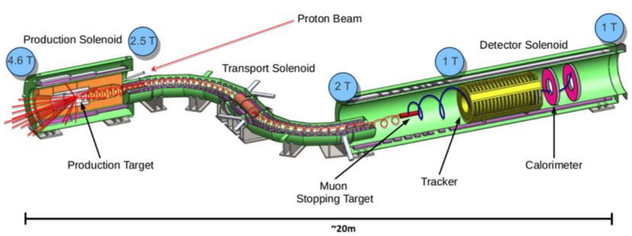
$$C^{1211}_{ledq}/\Lambda^2 < \left(2.2 \times 10^3 \text{ TeV}\right)^{-2}$$

Fernández-Martínez, et al., 2403.09772 (EPJC)

Semileptonic four-fermion operator

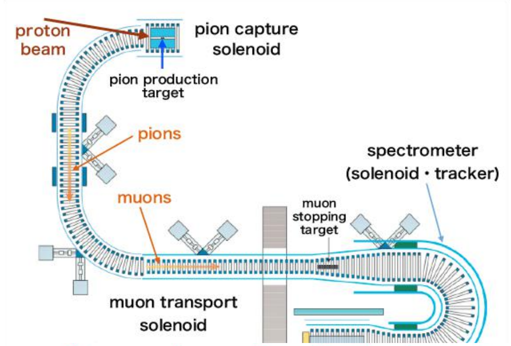
Lepton flavor violating (LFV) scenario

Mu2e (Fermilab):



commissioning starts in early 2025

COMET (J-PARC):

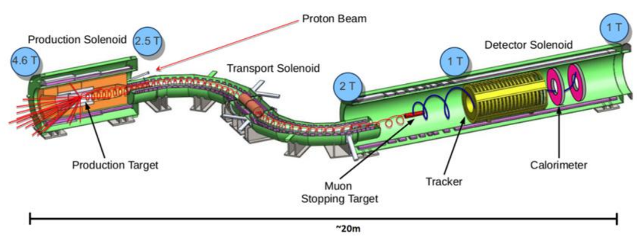


✓Proton beamline (C-Line) ready.
✓Muon transport solenoid ready.
- Pion capture solenoid still under preparation.

Semileptonic four-fermion operator

Lepton flavor violating (LFV) scenario

Mu2e (Fermilab):



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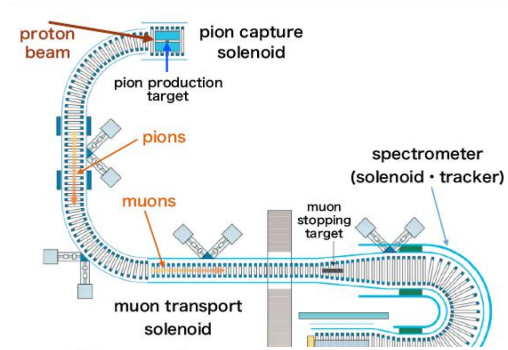

✓Proton beamline (C-Line) ready.
✓Muon transport solenoid ready.
• Pion capture solenoid still under preparation.

Using expected sensitivity:

$$\mathrm{CR}\left(\mu^- + \mathrm{Al} \to e^- + \mathrm{Al}\right) < 10^{-17}$$

$$\Rightarrow \quad C_{ledq}^{1211}/\Lambda^2 < \left(2.9 \times 10^4 \ \mathrm{TeV}\right)^{-2}$$

extraordinarily sensitive probe of new physics

W. Haxton et al., 2406.13818

Two questions

- In the LFC scenario:

$$C_{ledq}^{2211}/\Lambda^2 = (0.017 \pm 0.039)\ \mathrm{TeV}^{-2} \quad \text{(current)}$$

How to uncover the relevant new physics?

- In the LFV scenario:

$$C_{ledq}^{1211}/\Lambda^2 < \left(2.2 \times 10^3\ \mathrm{TeV}\right)^{-2} \quad \text{(current)}$$

$$C_{ledq}^{1211}/\Lambda^2 < \left(2.9 \times 10^4\ \mathrm{TeV}\right)^{-2} \quad \text{(future)}$$

How to alleviate the mass scale of new physics?

Two questions

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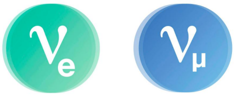

How to uncover the relevant new physics?

$$L_\alpha = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}_\alpha$$

➡ measuremets of neutrino non-standard interactions

- In the LFV scenario:

$$C_{ledq}^{1211}/\Lambda^2 < \left(2.2 \times 10^3\ \text{TeV}\right)^{-2} \quad \text{(current)}$$

$$C_{ledq}^{1211}/\Lambda^2 < \left(2.9 \times 10^4\ \text{TeV}\right)^{-2} \quad \text{(future)}$$

How to alleviate the mass scale of new physics?

➡ four-fermion interaction from dark loop

Neutrino Non-Standard Interactions

Charged-current neutrino NSIs:

$$\mathcal{L}_{\rm CC} \supset -\frac{2V_{ud}}{v^2}\left\{\frac{1}{2}\left[\epsilon_S\right]^{ij}_{\alpha\beta}\left(\bar{u}_i d_j\right)\left(\bar{\ell}_\alpha P_L \nu_\beta\right) - \frac{1}{2}\left[\epsilon_P\right]^{ij}_{\alpha\beta}\left(\bar{u}_i \gamma_5 d_j\right)\left(\bar{\ell}_\alpha P_L \nu_\beta\right) + \text{ h.c. }\right\}$$

$$\frac{C^{2211}_{ledq*}}{\Lambda^2} = \frac{-2V_{ud}}{v^2}\left[\epsilon_S\right]^{11}_{22} = \frac{-2V_{ud}}{v^2}\left[\epsilon_P\right]^{11}_{22}$$

$\delta\Gamma\left(\pi^+ \to \mu^+ \nu_\mu\right)$ modifies the neutrino sources

$$\approx \frac{\left(\left(m_\pi^2 - m_\mu^2\right)^2 m_\mu^2\right)^2 f_\pi^2}{64\pi m_\pi^3}\left|J_{\pi\mu}\left(\frac{V_{ud}}{v^2}\left[\epsilon_P\right]^{11}_{22}\right)^2\right|^2$$

$$J_{\pi\mu} = \frac{m_\pi^2}{m_\mu\left(m_u + m_d\right)} \sim 20$$

Neutrino Non-Standard Interactions

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$$J_{\pi\mu} = \frac{m_\pi^2}{m_\mu\left(m_u + m_d\right)} \sim 20$$

Next-generation oscillation experiments

	Operator	T2HK limit (TeV)	DUNE limit (TeV)	JUNO limit (TeV)	T2HK and DUNE limit (TeV)	JUNO and TAO limit (TeV)
ν_μ	$\mathcal{O}_{ledq_{2211}}$	9.1	11.2	0.7	12.3	0.7
ν_e	$\mathcal{O}_{ledq_{1211}}$	454.2	19.3	1.2	454.2	1.2

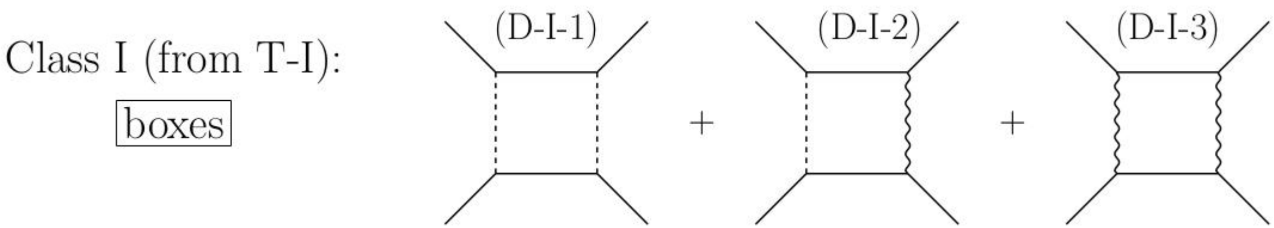
Among the most sensitive LFC operators to probe:

$$C^{2211}_{ledq}/\Lambda^2 < (12.3\ \text{TeV})^{-2}$$

Y. Du, H.-L. Li, J. Tang, S. Vihonen, J.-H. Yu 2106.15800 (PRD)

Dark loop

UV completions of four-fermion operators



dark particles in box diagram

Cepedello, Esser, Hirsch, Sanz, 2302.03485 (JHEP)

D-I-1 provides the simplest realizetion for

$$O_{ledq}^{\alpha\beta st} = \left(\bar{L}_{\alpha}^{j} e_{R\beta}\right)\left(\bar{d}_{Rs} Q_{t}^{j}\right)$$

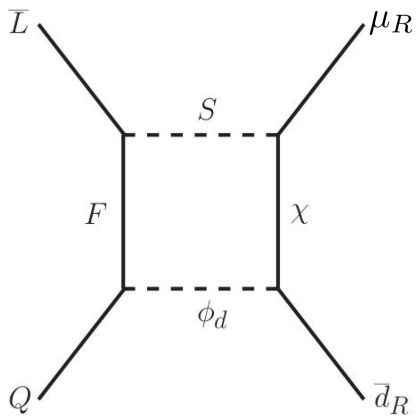
$$(\alpha, \beta) = (2,2)\,,(1,2) \qquad s = t = 1$$

Two key points to alleviate the new physics scale:

- loop factor $\sim 1/16\pi^2$
- coupling dependence $\sim f_{\rm NP}^4$

Fermion portal dark matter

UV completion with dark particles



new fields	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	Z_2
χ	$\mathbf{1}$	$\mathbf{1}$	0	-1
F	$\mathbf{1}$	$\mathbf{2}$	$\frac{1}{2}$	-1
S	$\mathbf{1}$	$\mathbf{1}$	1	-1
ϕ_d	$\mathbf{3}$	$\mathbf{1}$	$-\frac{1}{3}$	-1

$$\mathcal{L} = f_{LS}\left(\bar{L}F_R\right)S^* + f_{\chi S}\left(\bar{\chi}_L\mu_R\right)S + f_{FQ}\left(\bar{F}_R Q\right)\phi_d^* + f_{d\chi}\left(\bar{d}_R\chi_L\right)\phi_d + \text{ h.c.}$$

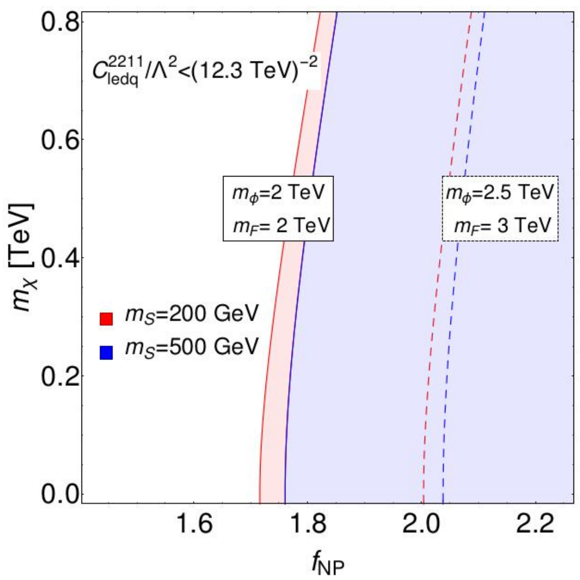
Majorana DM: χ
mediators: $S,\ \phi_d$
lepton: F

$$f_{\rm NP} \equiv \left(f_{LS}f_{\chi S}f_{FQ}f_{d\chi}\right)^{1/4}$$

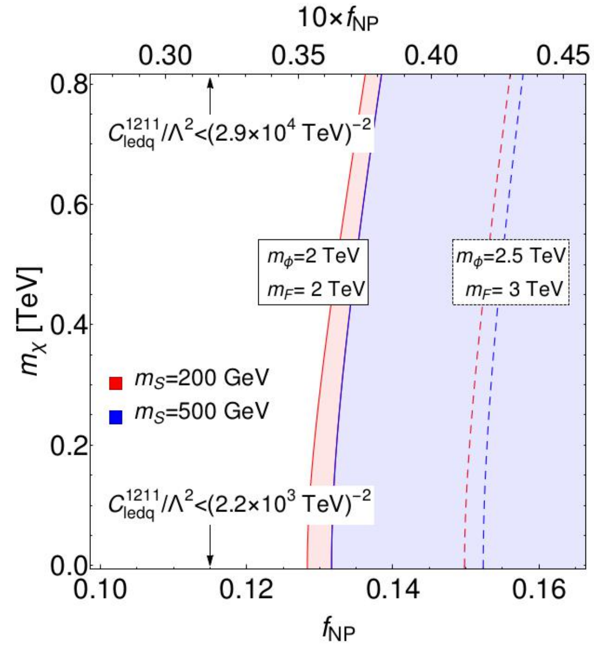
Cepedello, Esser, Hirsch, Sanz, 2302.03485 (JHEP)
An, Wang and H. Zhang, 1308.0592 (PRD)
Bai, Berger, 1308.0612 (JHEP)
DiFranzo, Nagao, Rajaraman, Tait, 1308.2679 (JHEP)

Wilson coeffcients

Model-indepdent constraints



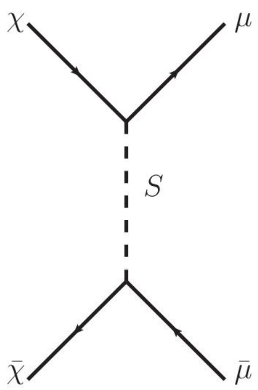
$f_{\rm NP} \sim 2$

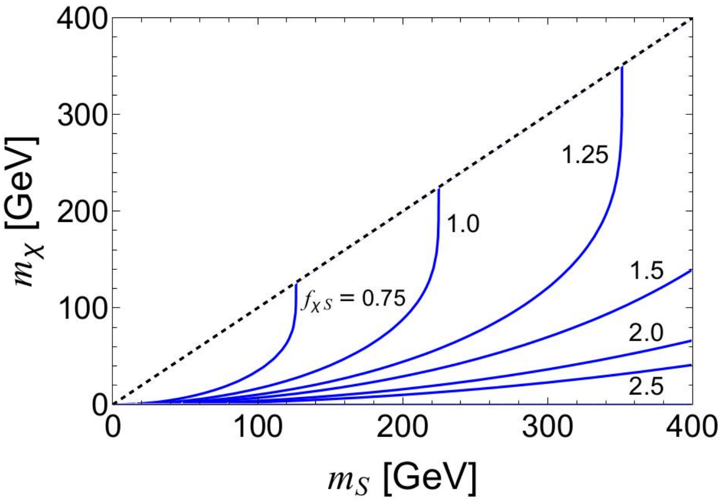


$f_{\rm NP} \sim 0.04 - 0.15$

DM relic density

Majorana DM annihilation at tree-level





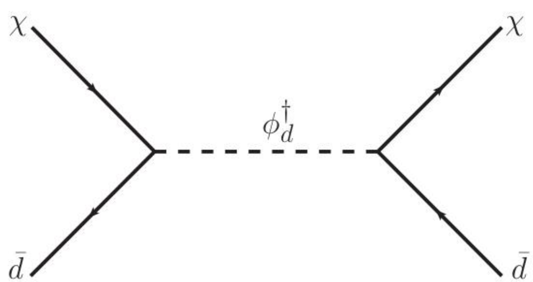
$$\langle \sigma v \rangle = \frac{f_{\chi S}^4}{32\pi} \frac{m_\mu^2}{m_S^4} \frac{1}{(1+x)^2} + v^2 \frac{f_{\chi S}^4}{48\pi m_S^2} \frac{x\left(1+x^2\right)}{(1+x)^4}$$

$$x \equiv m_\chi^2/m_S^2 \qquad m_\mu^2/m_S^2 \ll v^2$$

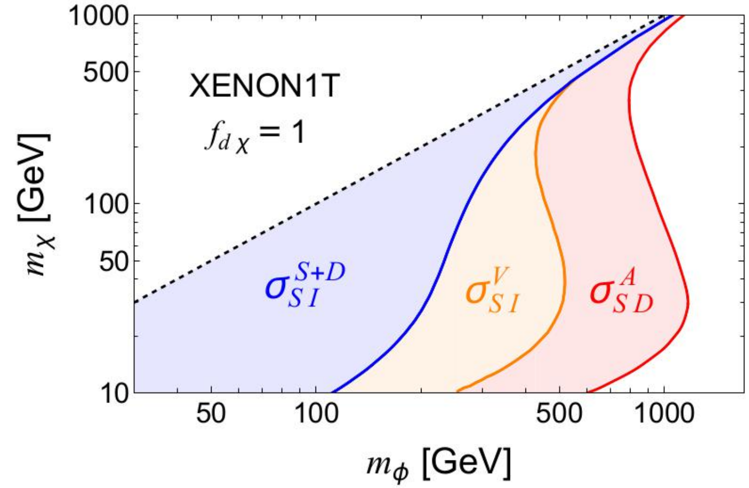
p-wave contribution is dominant

DM direct detection

Majorana DM scattering at tree-level



$$\chi\bar{d} \to \chi\bar{d}$$



Effective interactions:

$$\mathcal{O}_V = \left(\bar{\chi}\gamma^\mu\gamma^5\chi\right)\left(\bar{d}\gamma_\mu d\right) \qquad \mathcal{O}_S = m_d\bar{\chi}\chi\bar{d}d$$

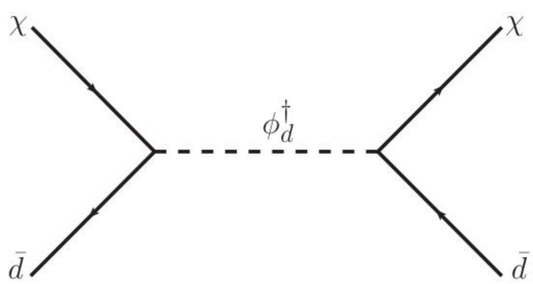
$$\mathcal{O}_A = \left(\bar{\chi}\gamma^\mu\gamma^5\chi\right)\left(\bar{d}\gamma_\mu\gamma^5 d\right) \qquad \mathcal{O}_D = \left[\bar{\chi}i\left(\partial^{\{\mu}\gamma^{\nu\}}\right)\chi\right]\left[\bar{d}\left(\gamma^{\{\mu}iD_-^{\nu\}} - \frac{g^{\mu\nu}}{4}i\not{D}_-\right)d\right]$$

K. A. Mohan, D. Sengupta, T. M. P. Tait, B. Yan, C. P. Yuan, 1903.05650 (JHEP)

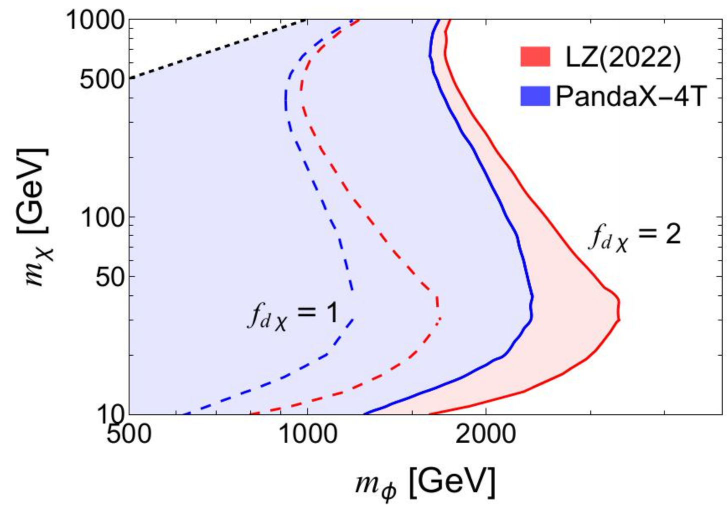
Exclusion limit from DM direct detection is dominated by SD interactions associated with $\mathcal{O}_A$

DM direct detection

Majorana DM scattering at tree-level



$$\chi\bar{d} \to \chi\bar{d}$$



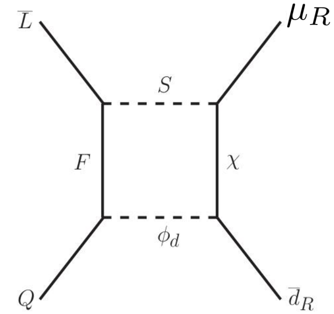
- The relic density of χ as the observed total DM relic density is assumed
- Limits could be notably weaker if the relic density depends on a give $f_{\chi S}$

Benchmarks:

$f_{d\chi} = 1, \quad m_\phi = 2$ TeV ⇨ no exclusion

$f_{d\chi} = 2, \quad m_\phi = 2.5$ TeV ⇨ 15 GeV $< m_\chi < 100$ GeV is excluded

Collider searches

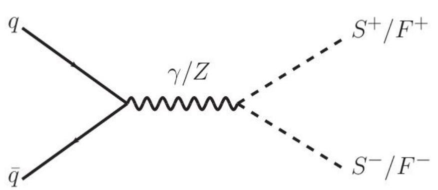


Leptons + MET: $m_F \geq m_\phi > m_S > m_\chi$

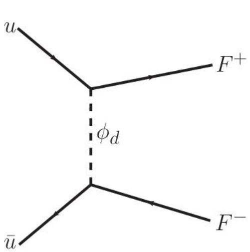
✔ SL1: $pp \to S^+S^-$, $S^\pm \to \mu^\pm\chi$;

SL2: $pp \to F^+F^-$, $F^+ \to S^+\nu_\ell$, $F^- \to S^-\bar{\nu}_\ell$, $S^\pm \to \mu^\pm\chi$;

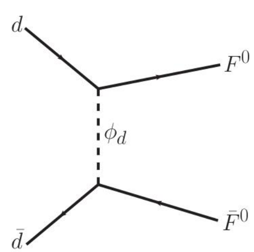
SL3: $pp \to F^0\bar{F}^0$, $F^0 \to S^+\ell^-$, $\bar{F}^0 \to S^-\ell^+$, $S^\pm \to \mu^\pm\chi$, $\ell = e$ or μ.



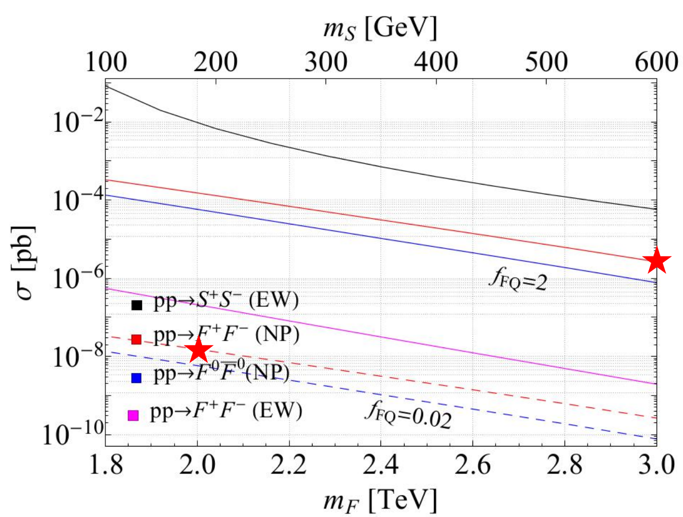
SL1, SL2



SL2



SL3



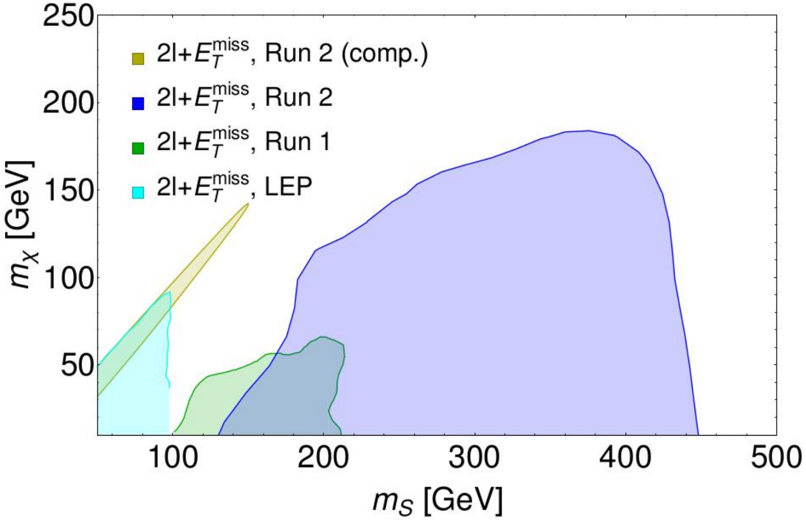
- SL2 and SL3 are negligible given m_F ★
- Only muons are in the final state

Collider searches

Leptons + MET: $m_F \geq m_\phi > m_S > m_\chi$

SL1: $pp \to S^+S^-,\ S^\pm \to \mu^\pm \chi;$ in both LFC and LFV scenarios

We read off the exclusion limits on the masses of right-handed slepton (smuon) and neutralino and reinterpret them as



see also

J. Liu, X.-P. Wang, K.-P. Xie, 2104.06421 (JHEP)
Q.-H. Cao, GL, K.-P. Xie, J. Zhang, 1711.02113 (PRD)

Collider searches

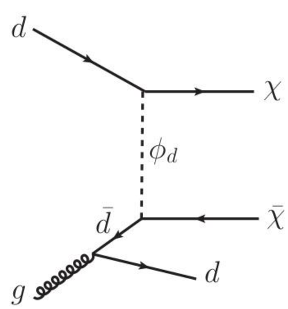
Jet(s) + MET: $m_F \geq m_\phi > m_S > m_\chi$

SJ1: $pp \to \chi\bar{\chi}j$ (3-body), $j = g,\ d$ or $\bar{d}$;

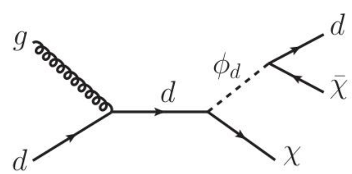
SJ2: $pp \to \phi_d^{\pm 1/3}\chi,\ \phi_d^{\pm 1/3} \to \bar{\chi}j$;

SJ3: $pp \to \phi_d^{+1/3}\phi_d^{-1/3},\ \phi_d^{\pm 1/3} \to \chi j$;

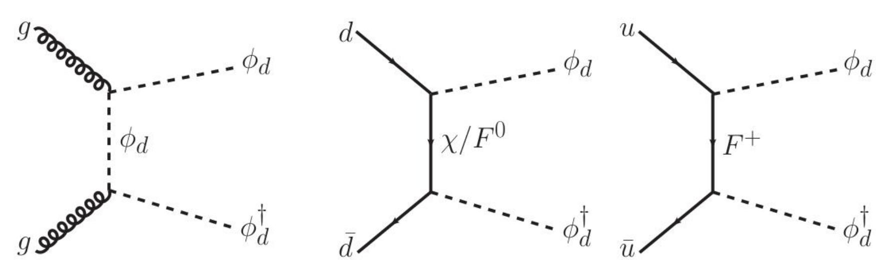
parton level:



SJ1



SJ2



SJ3

Collider searches

Jet(s) + MET: $m_F \geq m_\phi > m_S > m_\chi$

SJ1: $pp \to \chi\bar{\chi}j$ (3-body), $j = g$, d or $\bar{d}$;

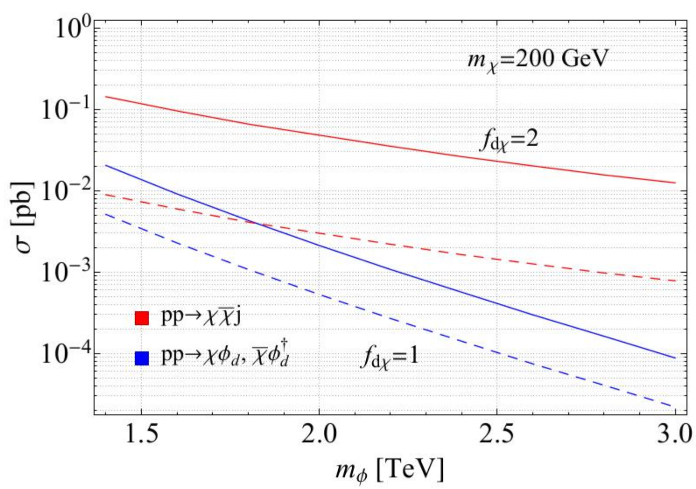
SJ2: $pp \to \phi_d^{\pm 1/3}\chi$, $\phi_d^{\pm 1/3} \to \bar{\chi}j$;

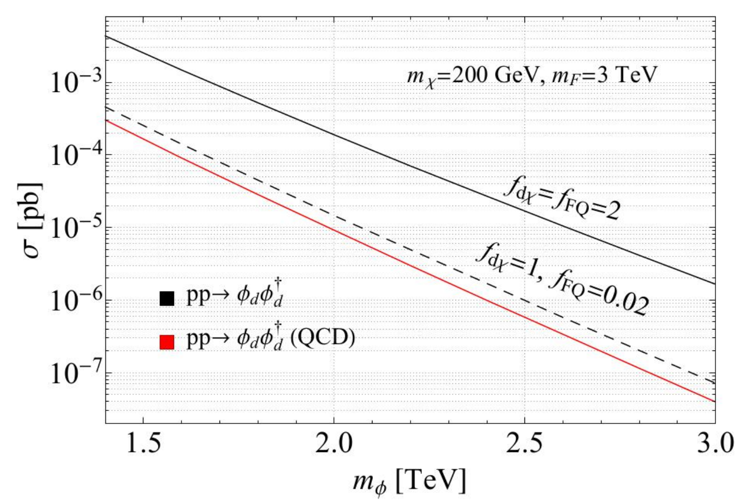
SJ3: $pp \to \phi_d^{+1/3}\phi_d^{-1/3}$, $\phi_d^{\pm 1/3} \to \chi j$;

monojet+MET search (SJ1, SJ2)

dijet+MET search (SJ2, SJ3)

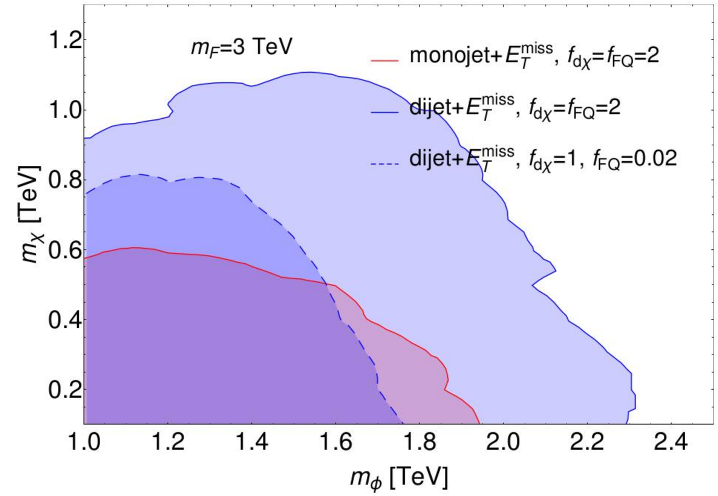
parton level:





Collider searches

Jet(s) + MET at LHC Run 2:



monojet+MET search :

- $\not{E}_T > 200$ GeV, leading jet $p_T > 150$ GeV and $|\eta| < 2.4$;
- up to four jets with $p_T > 30$ GeV and $|\eta| < 2.8$;
- $|\Delta\phi(\text{jet}, \not{p}_T)| > 0.4\ (0.6)$ for $\not{E}_T > 250$ GeV (< 250 GeV);
- veto of electron, muon, τ-lepton or photon.

dijet+MET search:

- $\not{E}_T > 300$ GeV, leading jet with $p_T(j_1) > 200$ GeV and sub-leading jet with $p_T(j_2) >$ 50 GeV, and $|\Delta\phi(j_{1,2,(3)}, \not{p}_T)| > 0.2$;
- $m_{\text{eff}} > 800$ GeV;
- veto of electron (muon) with $p_T > 6(7)$ GeV,

$$f_{d\chi} = 1,\ m_\phi \geq 1.76\ \text{TeV}$$

$$f_{d\chi} = f_{FQ} = 2,\ m_\phi \geq 2.3\ \text{TeV}$$

Combined results

Benchmark scenarios:

BM	m_ϕ[TeV]	m_F [TeV]	$f_{LS} = f_{FQ}$	$f_{d\chi}$	$f_{\chi S}$	$\Omega_\chi h^2$
(a)	2.5	3.0	2.1	2.0	2.0	/
(b)	2.5	3.0	2.1	2.0	/	0.1199
(c)	2.0	2.0	1.41×10^{-2}	1.0	1.5	/
(d)	2.0	2.0	1.41×10^{-2}	1.0	/	0.1199

$$f_{\rm NP} \equiv (f_{LS} f_{\chi S} f_{FQ} f_{d\chi})^{1/4}$$

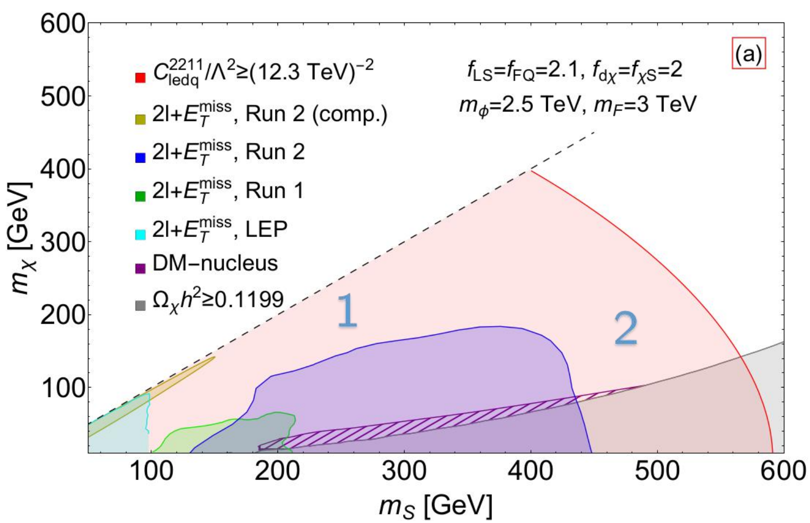
$f_{\rm NP} = 2.05$ (LFC)

$f_{\rm NP} = 0.1314$ (LFV)

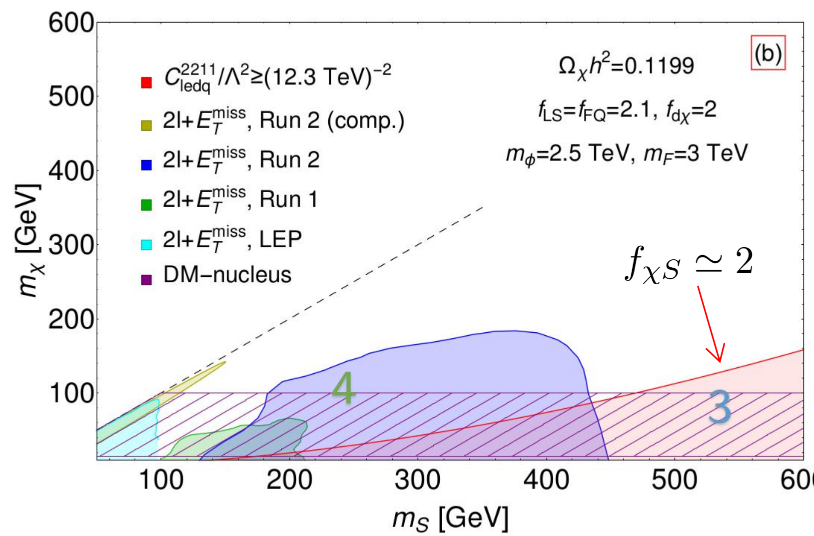
from collider searches and DM direct detection

Combined results

LFC scenarios:



$$\Omega_\chi h^2 \leq 0.1199$$



$$\Omega_\chi h^2 = 0.1199$$

1: compressed mass region
2: large m_S and m_χ region
} neutrino NSI

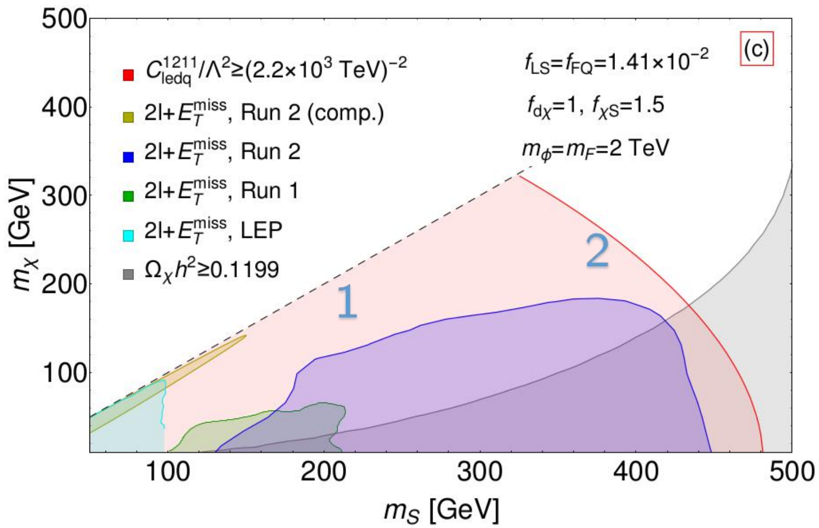
3: large m_S, small m_χ region → neutrino NSI and DM DD

4: EW m_S and m_χ region → LHC and DM DD

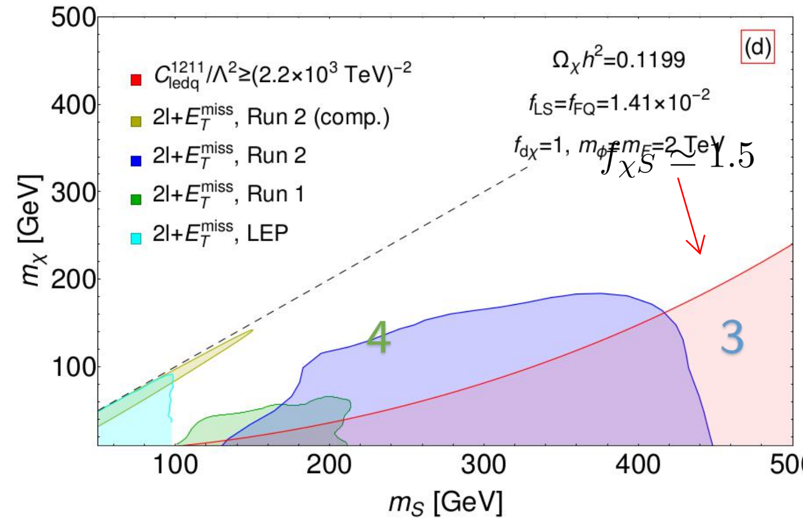
Combined results

LFV scenarios:

- no constraint from current DM direct detection
- sensitive to much smaller new physics couplings (f_{LS}, f_{FQ})



$\Omega_\chi h^2 \leq 0.1199$



$\Omega_\chi h^2 = 0.1199$

1: compressed mass region

2: large m_S and m_χ region

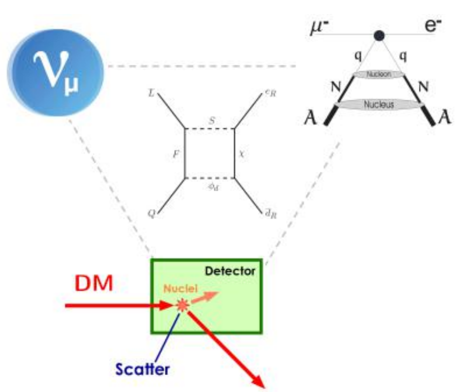
3: large m_S, small m_χ region

→ $\mu \to e$ conversion (regions 1–3)

4: EW m_S and m_χ region → LHC

Summary

- We have studied the interplay of neutrino, dark matter and cLFV
- We find that
  - neutrino NSIs measured in next-generation oscillation experiments could uncover LFC new physics
  - dark loop could significantly alleviate the mass scale of LFV new physics
  - model-independent constraints on the Wilson coefficients offer a distinctive probe of the fermion portal DM model, especially in the compressed mass region



muon collider

BM	m_ϕ[TeV]	m_F [TeV]	$f_{LS} = f_{FQ}$	$f_{d\chi}$	$f_{\chi S}$	$\Omega_\chi h^2$
(a)	2.5	3.0	2.1	2.0	2.0	/
(b)	2.5	3.0	2.1	2.0	/	0.1199
(c)	2.0	2.0	1.41×10^{-2}	1.0	1.5	/
(d)	2.0	2.0	1.41×10^{-2}	1.0	/	0.1199