

# $Z'$ -mediated Majorana dark matter: suppressed direct-detection rate and complementarity of LHC searches

Martin Gorbahn  
(University of Liverpool)

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T. Alanne, F. Bishara, J. Fiaschi, O. Fischer and U. Moldanazarova

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# Direct Detection EFTs for WIMPs

- ▶ Interpret improving direct detection results
- ▶ Tower of dark Matter EFTs [References in 2203.08204]:
  - ▶ Compare results for different target materials
  - ▶ Connect to collider and indirect searches
- ▶ Different model scenarios [See again 2203.08204]:
  - ▶ Spin-independent scattering  $(\bar{\chi}\chi)(\bar{q}q)$ ,  $(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)$ ,  $(\bar{\chi}\chi)(GG)$
  - ▶ Spin-dependent  $\vec{S}_\chi \cdot \vec{S}_N$  difficult to generate on its own
  - ▶ Gluophilic pseudoscalar mediator
  - ▶ Magnetic Dipole DM
  - ▶ Vector mediator for Majorana DM [This Talk]

# Content

- ▶ Introduction: Direct detection and Majorana dark matter with vector mediator
- ▶ Bottom up: NR EFT → DMWET →  $SU(2) \times U(1)$  (DMEFT) → Model
- ▶ Collider Constraints
- ▶ Conclusions

# Direct Detection

- ▶ The interaction rate per unit mass is given by [Lewin & Smith Astropart. Phys. 6 (1996)]

$$R = \frac{\Gamma}{m_A} = \frac{1}{m_A} \langle n_\chi \sigma v \rangle = \frac{\rho_\chi}{m_A m_\chi} \langle \sigma v \rangle$$

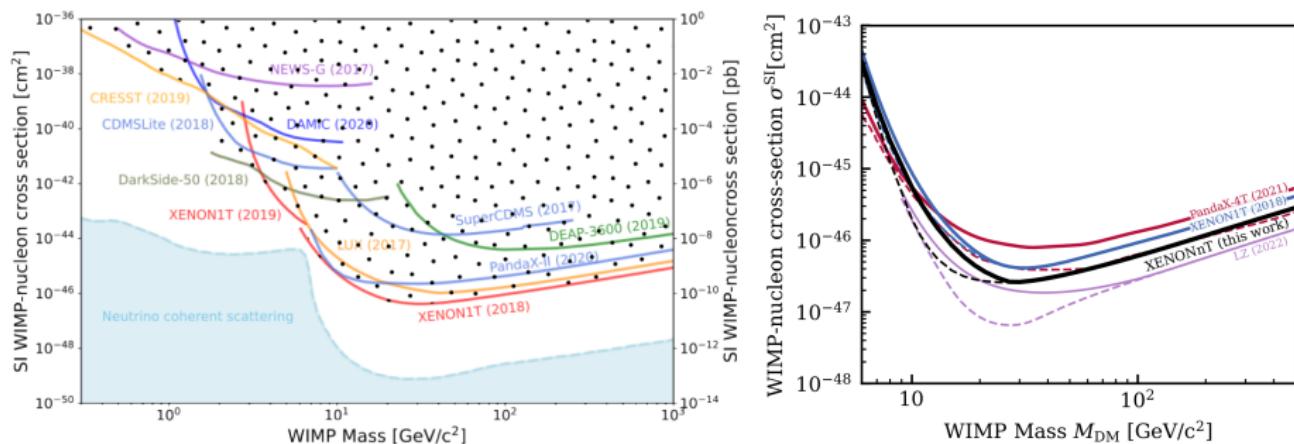
- ▶ Interested in  $dR/dE_R$  (but must convolve with exp. eff.)

$$\frac{dR}{dE_R} = \frac{\rho_\chi}{m_A m_\chi} \left\langle \frac{d\sigma}{dE_R} v \right\rangle$$

- ▶ Finally, we have

$$\frac{dR}{dE_R} = \frac{\rho_\chi}{m_A m_\chi} \int_{v_{\min}} dv f(v) \frac{d\sigma}{dE_R} v$$

# Status of Direct Searches



- ▶ PDG 2022 Review
- ▶ Updates from LZ 22 and XENONnT 23
  - ▶ Rejection power [EPJC 91, 907] and discovery power

## Combination with collider constraints

- ▶ The spin independent constraints depend on the efficiencies at different recoils
- ▶ While some models (Higgs mediation) give spin independent cross sections,
- ▶ others do not and lead to different recoil spectrum
- ▶ Specific model → DMEFT → DMWET → non relativistic Galilean invariant theory
  - ▶ DirectDM [1708.02678]

# Majorana vector interaction

- One Weyl fermion,  $\chi$ , charged under  $U(1)'$

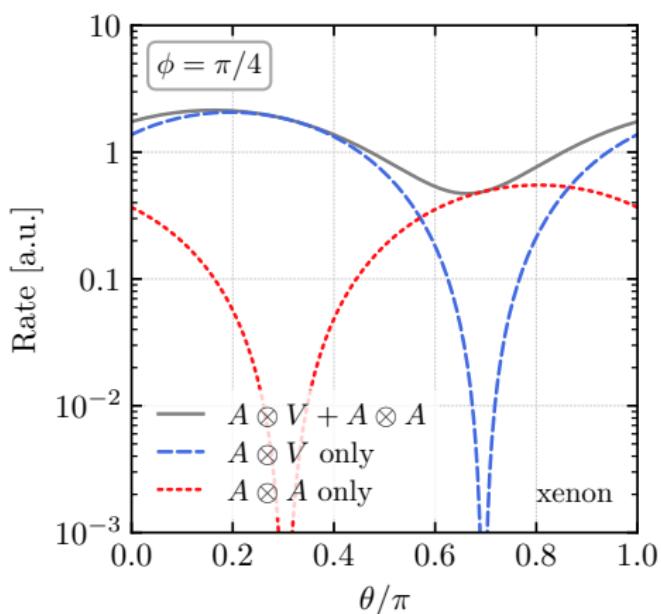
$$\mathcal{L}_{U(1)'} = \sum_{f=Q,u,d,L,e,\chi} \bar{f} iD_\mu \sigma^\mu f + (D_\mu S)^\dagger D^\mu S - \left[ \frac{1}{2} y_\chi \chi \chi S + h.c. \right]$$

- Assume, for now, isospin limit ( $Q'_u = Q'_d$ ):

$$► A \otimes V_{u+d} = (\bar{\chi} \gamma_\mu \gamma_5 \chi) [\bar{u} \gamma^\mu u + \bar{d} \gamma^\mu d]$$

$$► A \otimes A_{u+d} = (\bar{\chi} \gamma_\mu \gamma_5 \chi) [\bar{u} \gamma^\mu \gamma_5 u + \bar{d} \gamma^\mu \gamma_5 d]$$

# Isospin limit



$A \otimes V_{u+d}$ : velocity suppression

$A \otimes A_{u+d}$ : spin suppression

(nuclear spin from outer shell  
→ no coherent enhancement)

Define linear combination:

$$\left(\frac{s_\theta}{\sqrt{2}} - c_\theta\right) A \otimes A - \left(\frac{s_\theta}{\sqrt{2}} + c_\theta\right) A \otimes V$$

Both  $A \otimes V_{u+d}$

and  $A \otimes A_{u+d}$  give comparable  
rate for Xenon target

# From the Bottom Up: NREFT

- ▶ Four Galilean invariant operators:

$$\begin{aligned} \mathcal{O}_4^{\text{NR}} &= \vec{S}_\chi \cdot \vec{S}_N, & \mathcal{O}_8^{\text{NR}} &= \vec{S}_\chi \cdot \vec{v}^\perp, \\ \mathcal{O}_6^{\text{NR}} &= (\vec{S}_\chi \cdot \vec{q})(\vec{S}_N \cdot \vec{q}), & \mathcal{O}_9^{\text{NR}} &= i\vec{S}_\chi \cdot (\vec{S}_N \times \vec{q}), \end{aligned}$$

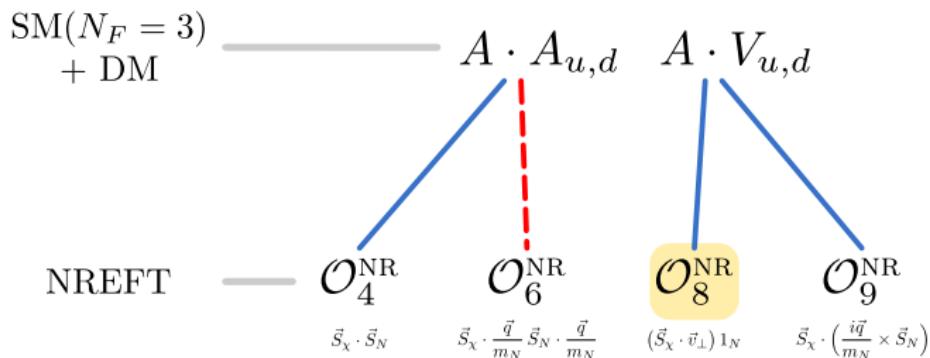
- ▶  $\mathcal{O}_{6,8,9}$  velocity & momentum suppressed (i.e.  $\mathcal{O}_8 = 0$  for  $v=0$ )
- ▶  $\mathcal{O}_8$  coherently enhanced (i.e. by # of u's and d's in Xe)
- ▶  $\mathcal{O}_{4,8}$  and  $\mathcal{O}_{6,9}$  are P-even and P-odd respectively

NREFT	—	$\mathcal{O}_4^{\text{NR}}$ $\vec{S}_\chi \cdot \vec{S}_N$	$\mathcal{O}_6^{\text{NR}}$ $\vec{S}_\chi \cdot \frac{\vec{q}}{m_N} \vec{S}_N \cdot \frac{\vec{q}}{m_N}$	$\mathcal{O}_8^{\text{NR}}$ $(\vec{S}_\chi \cdot \vec{v}_\perp) 1_N$	$\mathcal{O}_9^{\text{NR}}$ $\vec{S}_\chi \cdot \left( \frac{i\vec{q}}{m_N} \times \vec{S}_N \right)$
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 = Coherently enhanced

# From the Bottom Up: WET

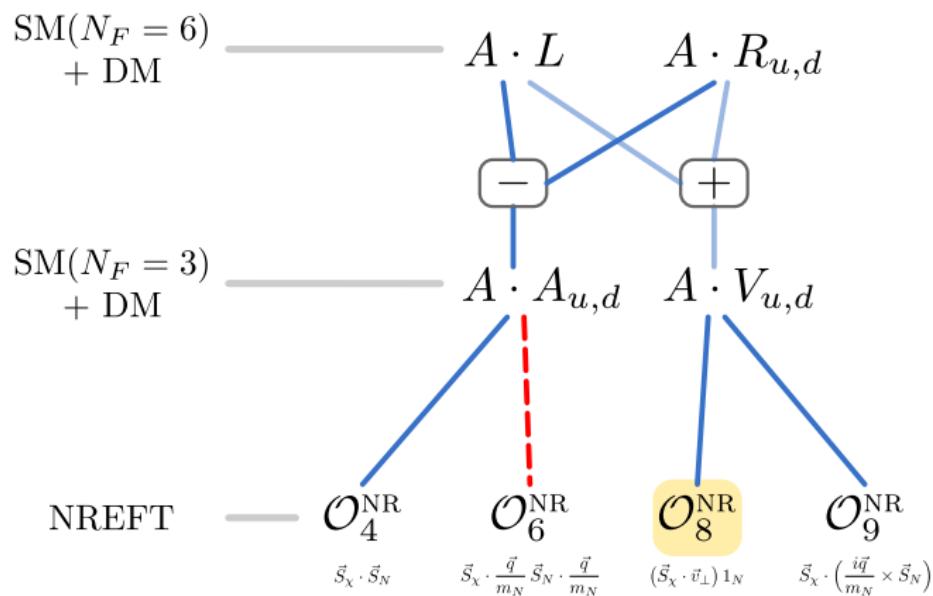
- ▶  $A \otimes A_{u,d}$  match onto the P-even Operators  $\mathcal{O}_{4,8}$
- ▶  $A \otimes V_{u,d}$  match onto the P-odd Operators  $\mathcal{O}_{6,9}$
- ▶  $\mathcal{O}_4$  is not velocity suppressed
- ▶  $\mathcal{O}_8$  is velocity suppressed but coherently enhanced



= Coherently enhanced

# From the Bottom Up: $SU(2) \times U(1)$

$$Q_{6,i}^{(6)} = (\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{Q}_L\gamma^\mu Q_L), \quad Q_{7,i}^{(6)} = \dots(\bar{u}_R\gamma^\mu u_R), \quad Q_{8,i}^{(6)} = \dots(\bar{d}_R\gamma^\mu d_R)$$



= Coherently enhanced

# Independent Parameters

- ▶ If we deviate from iso-spin limit:
  - ▶ we could cancel up against down in the  $O_8$  contribution
  - ▶ we could cancel the  $A \otimes A$  contribution to  $O_4$
- ▶ Can this be done at the same time?

$$(A \otimes V)_u : \quad \hat{C}_{2,u}^{(6)} = C_{7,1}^{(6)} + C_{6,1}^{(6)},$$

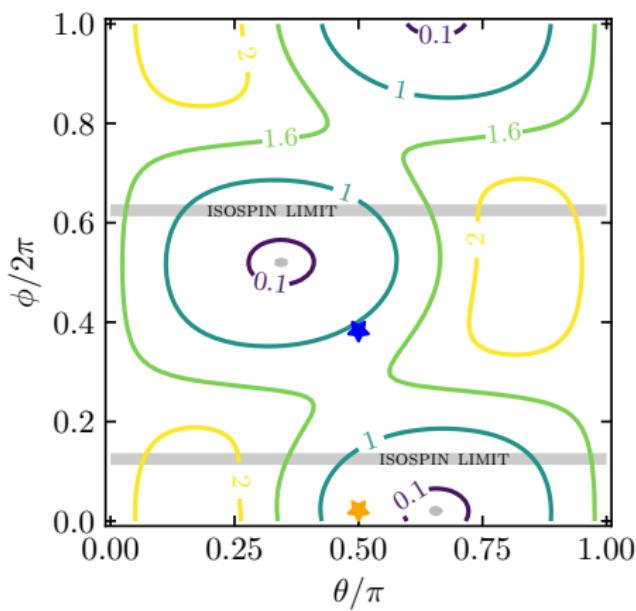
$$(A \otimes V)_d : \quad \hat{C}_{2,d}^{(6)} = C_{8,1}^{(6)} + C_{6,1}^{(6)},$$

$$(A \otimes A)_u : \quad \hat{C}_{4,u}^{(6)} = C_{7,1}^{(6)} - C_{6,1}^{(6)},$$

$$(A \otimes A)_d : \quad \hat{C}_{4,d}^{(6)} = C_{8,1}^{(6)} - C_{6,1}^{(6)}.$$

- ▶ It is possible to generate  $A \cdot V$  operators only
- ▶ but, if one wants to have isospin violation, then only **one** can be set to zero (e.g.,  $C_{A \cdot A_d} = 0$ ).

# Removing One Variable



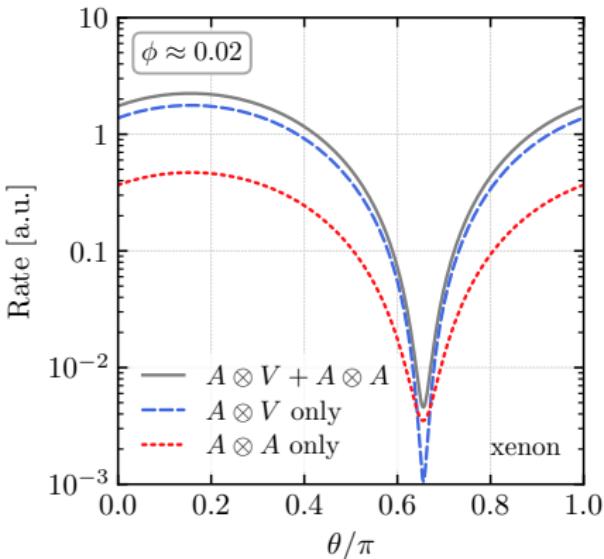
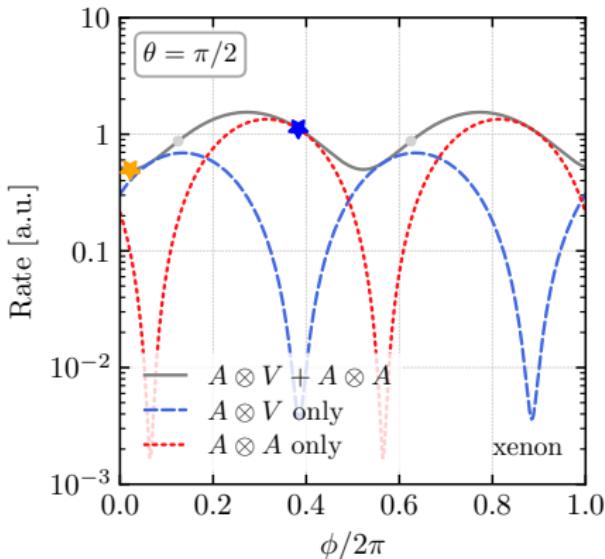
To simplify the analysis,  
use following parametrisation:

$$C_{6,1}^{(6)} \rightarrow \frac{g'^2}{\Lambda^2} \cos \theta$$

$$C_{7,1}^{(6)} \rightarrow \frac{g'^2}{\Lambda^2} \sin \theta \cos \phi$$

$$C_{8,1}^{(6)} \rightarrow \frac{g'^2}{\Lambda^2} \sin \theta \sin \phi$$

Now the  
sum of their squares =  $g'^4/\Lambda^4$   
→ removes one variable

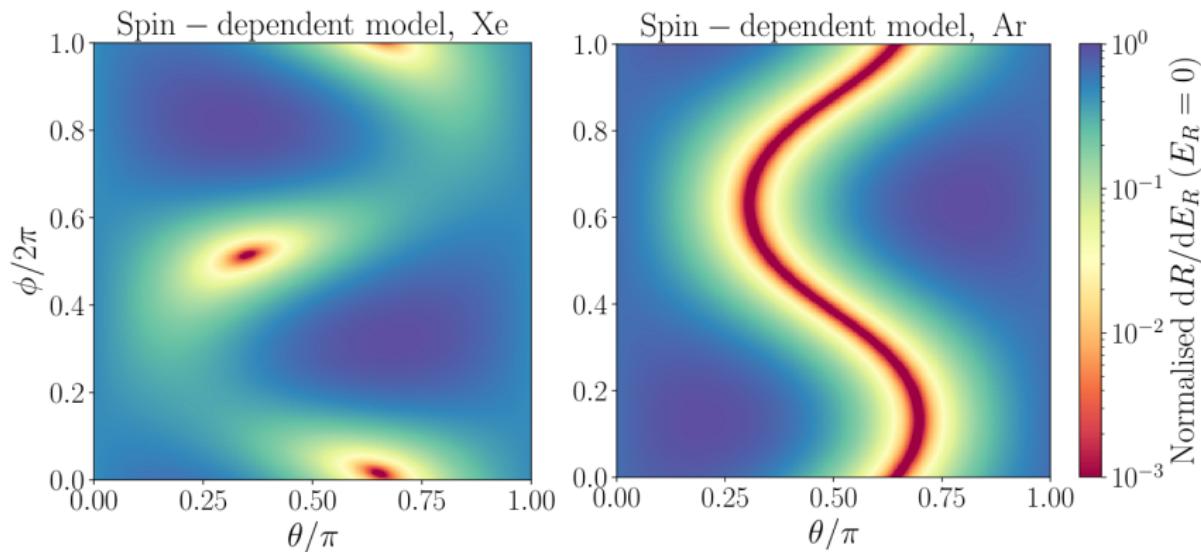


- ★  $A \otimes A$  suppressed, but  $A \otimes V$  gives contribution
- ★ Has a simple Anomaly free charge assignment:

$u_R$	$d_R$	$e_R$	$\chi_R$
-1	+1	+1	-1

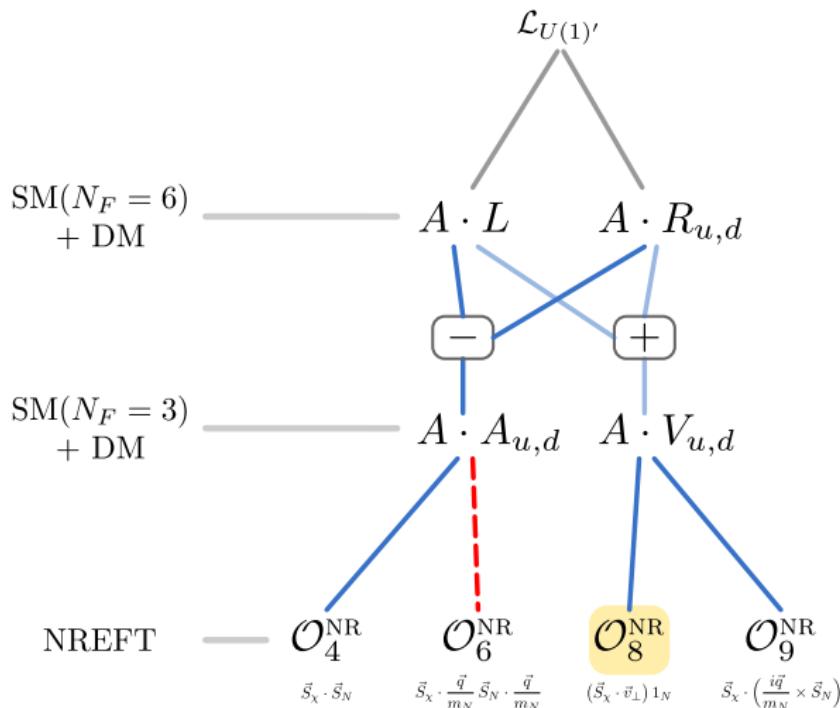
# Xenon and Argon

- Argon is lighter: velocity suppression of  $O_8^{NR}$  is not compensated
  - Only  $A \otimes A$  is relevant
- Minima in Xe plane are also suppressed for Ar



[Plots from 2302.05458, using the same parametrisation]

# From the Bottom Up: Model

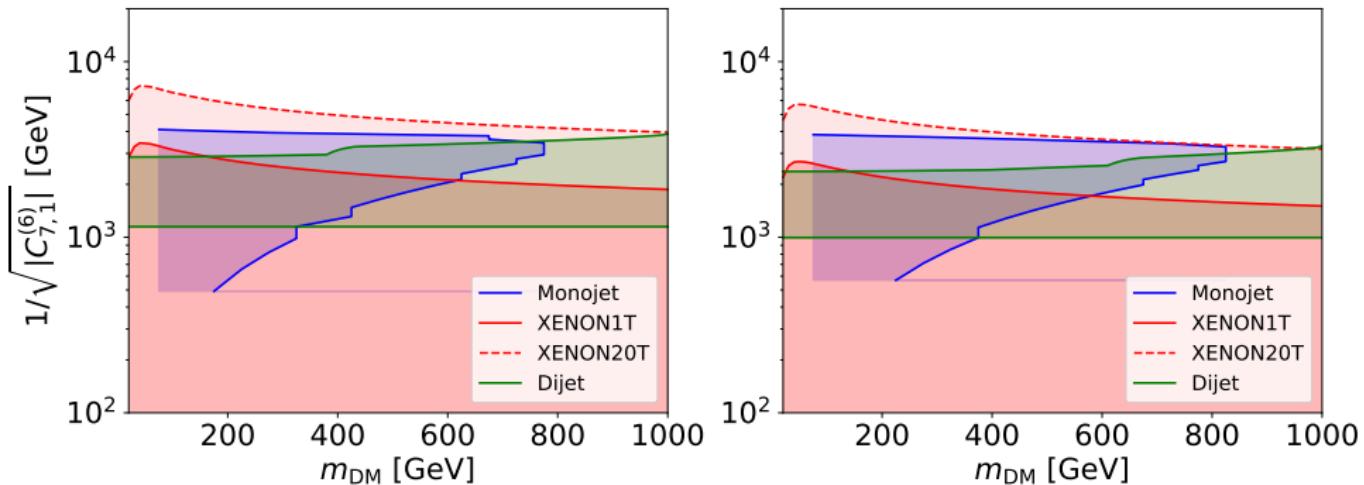


= Coherently enhanced

# Collider Constraints

- ▶ Monojet analysis reproduced (with some effort) from: [ATLAS, Phys. Rev. D 103, 112006 (2021)]
- ▶ Dijet limits obtained from:
  - ▶ Low mass region: [0.7, 2] TeV  $29.3 \text{ fb}^{-1}$  dataset [ATLAS, Phys. Rev. Lett. 121 081801 (2018)]
  - ▶ High mass region:  $> 2 \text{ TeV}$   $139 \text{ fb}^{-1}$  dataset [ATLAS, JHEP 03 145 (2020)]
- ▶ Ditaus limits recasted from: [ATLAS, JHEP 07 157 (2015)] the Mass region: [0.5, 2.5] TeV  $19.5 - 20.3 \text{ fb}^{-1}$  dataset

# Results



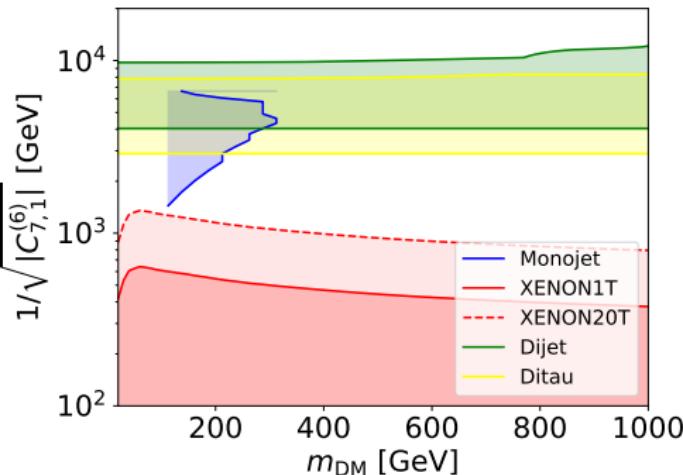
- ▶ left ★ and right ★ benchmark points have  $C_{6,1}^{(6)} = 0$
- ▶ presented in terms of  $1/\sqrt{|C_{7,1}^{(6)}|} = M_{Z'}/\sqrt{g_q g_\chi}$  ( $\sim 2M_{Z'}$  here)

# Minimal direct detection

- ▶ Minimises the direct detection rate:
  - ▶ Cancel up & down in Xe for  $A \otimes V$  and in outer shell of Xe for  $A \otimes A$
  - ▶ Anomaly free charge assignment

$Q_{L,1}^c$	$u_{R,1}$	$d_{R,1}$	$u_{R,2}$	$d_{R,2}$	$L_{L,3}^c$	$e_{R,3}$	$\chi_R$
$+\frac{1}{2}$	+1	0	0	-2	$-\frac{3}{2}$	0	3

# Results



- Use  $g_{q,\chi} = 0.1$
- Monojet limits are weakened
  - up to  $M_{Z'} \sim 1.2$  TeV (interaction strength)
  - up to  $M_\chi \sim 0.3$  TeV (extra decay channels)
- Dijet and ditaus searches
  - independent on  $m_\chi$
  - difficult for light  $Z'$

- $\sigma_{si}$  tree (model dependent) and loop induced

$$\frac{\sigma_{si}}{\sigma_{sd}} \sim A^2 \frac{g'^4}{(4\pi)^4} \frac{m_N^2 m \chi^2}{m_{Z'}^4} \sim O(10^{-11}),$$

- charge assignment will also generate D mixing

# How do I find my way back?

- ▶ Bottom up or top down?

# How do I find my way back?

- ▶ Bottom up or top down?



# Conclusions

- ▶ Models might not be realistic, but model independent constraints would be useful
- ▶ We assumed flat exp. efficiency
- ▶ Consider set of Wilson coefficients that occur in certain classes of models
- ▶ Limits on these set of Wilson coefficients (that include exp. eff.) could be combined with other searches
- ▶ There are still parameter regions where direct and collider searches give complementary information