Hunting for Hypercharge Anapole Dark Matter

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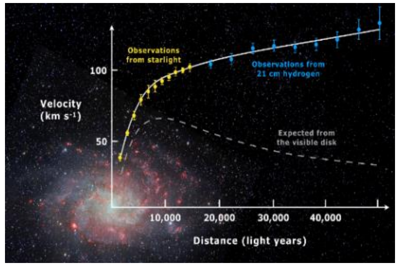
Introduction

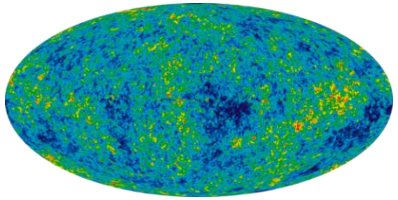
Dark Matter (DM)

Practical

Empirical evidence
(several but only *gravitationl*)

Galaxy rotation curves
Velocity dispersions
Galaxy clusters
Gravitational lensing
Cosmic microwave background
Structure formation
Bullet cluster
. . .





Conceptual

DM candidate
(explaining the evidence fully or parttially)

QCD axions
Axion-like particles
Fuzzy CDM

SM neutrinos
Sterlile neutrinos

Supersymmtry
Extra dimensions
Little Higgs
Simplified models
Effective field theories
. . .

Primordial black holes
MACHOs
Macros

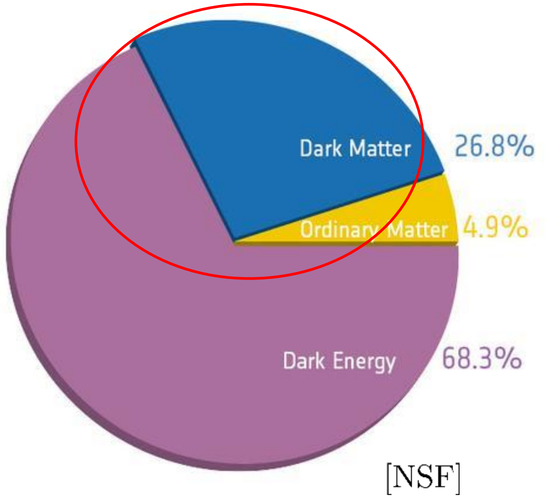
Strangelet
Superfluid vacuum theory
Dynamical dark matter

Modified Newtonian dynamics
Tensor-vector-scalar gravity
Entropic gravity
. . .

[Wikipedia, PDG]

Introduction

DM search crucial to
the search for new physics



Only *gravitational effect* of DM

↓

Electrically neutral and colorless

Our desperate conditions on the DM particle

A single (elementary or not) Majorana particle

$\oplus$

Standard Model (completed in 2012)

$SU(3)_C \times SU(2)_L \times U(1)_Y \Rightarrow SU(3)_C \times U(1)_{EM}$

valid at least up to several TeV scale

↓

Only allowed scenario

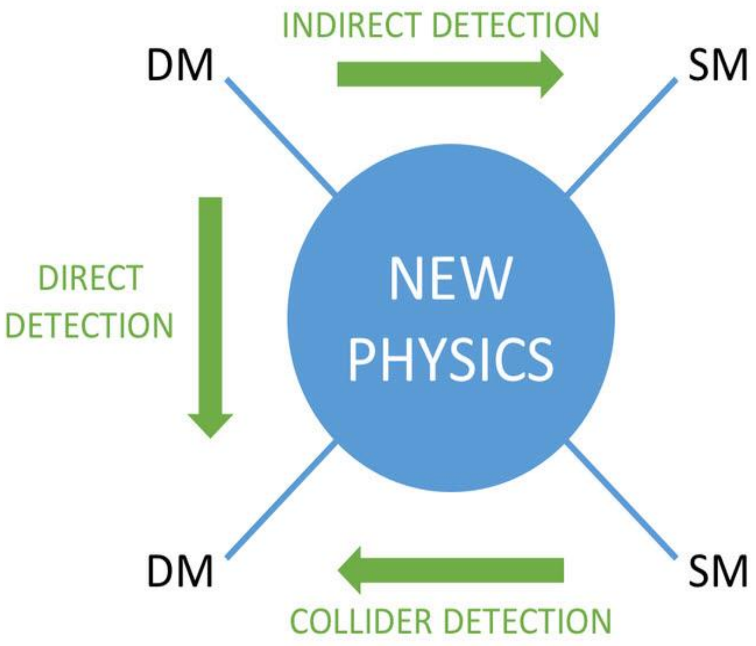
$U(1)_Y$ anapole DM particle

Intrinsic higher-dim EFT operators → Weak interaction rate

Mass : GeV $\sim$ a few TeV

Spin : $1/2,\ 1,\ 3/2,\ \cdots$

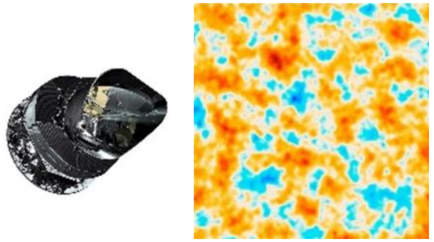
Complementary DM Hunting Strategies



[R. J. Wilkinson (2016)]

$\bigoplus$

A lot of ingenious probes



Planck

XENONnT

LHC

Indirect detection
(relic abundance)

DM + DM ⇒ SM + SM

Direct detection

DM + SM ⇒ DM + SM

Collider detection

SM + SM ⇒ DM + DM

$\bigoplus$

Conceptual constraints

Unitarity and perturbativity

Introduction

Studies including anapole DM			
	Spin-1/2 EM anapole	Spin-1 EM anapole	Spin-1/2 hypercharge anapole
Relic abundance	[C. M. Ho and R. J. Scherrer, PLB (2013)] ···		EM $\rightarrow$ Hypercharge [C. Arina, A. Cheek, K. Mimasu and L. Pagani, EPJC (2021)]
Direc detection	[M. Pospelov and T. ter Veldhuis, PLB (2000)] ···	[J. Hisano, A. Ibarra and R. Nagai, JCAP (2020)] ···	
Collider	[Y. Gao, C. M. Ho and R. J. Scherrer, PRD (2014)] ···		
Indirect detection	[C. M. Ho and R. J. Scherrer, PRD (2013)] ···		
UV completion	[L. G. Cabral-Rosetti, M. Mondragón and E. Reyes-Pérez, NPB (2016)] ···		

Generic analytic and numerical analysis of the hypercharge anapole DM particle of spin 1/2 and 1

Hunting target

Hypercharge anapole DM particle of any spin

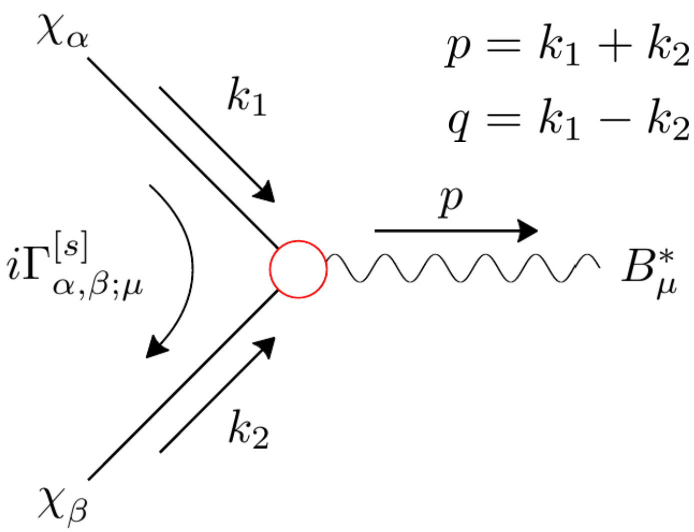
Construct general 3-point hypercharge anapole $\chi\chi B$ vertices by imposing U(1) hypercharge symmetry and identical particle (Majorana) conditions for any spin

Evaluate the relic abundance, production cross sections at the (HL-)LHC and direct detection rate at the XENONnT numerically for spin-1/2 and 1 Majorana particles

Combining the experimental results with a conceptual naïve perturbativity bound (NPD), we draw a unified picture for hunting for spin-1/2 and 1 hypercharge anapole DM.

Based on the picture, we make a simple educated guess for higher-spin anapole DM particles.

Constructing anapole vertices



$p = k_1 + k_2$

$q = k_1 - k_2$

U(1) gauge invariance

$\rightarrow \quad p^\mu \Gamma^{[s]}_{\alpha,\beta;\mu} = 0$

Identical-particle (IP) relation

$$\rightarrow \begin{cases} C\Gamma^{[s]}_{\beta,\alpha;\mu}(p,-q)C^{-1} = \Gamma^{[s]}_{\alpha,\beta;\mu}(p,q) & \text{for fermions} \\ \Gamma^{[s]}_{\beta,\alpha;\mu}(p,-q) = \Gamma^{[s]}_{\alpha,\beta;\mu}(p,q) & \text{for bosons} \end{cases} \qquad (C = i\gamma^2\gamma^0)$$

$\alpha \equiv \alpha_1 \cdots \alpha_n$

$\beta \equiv \beta_1 \cdots \beta_n$

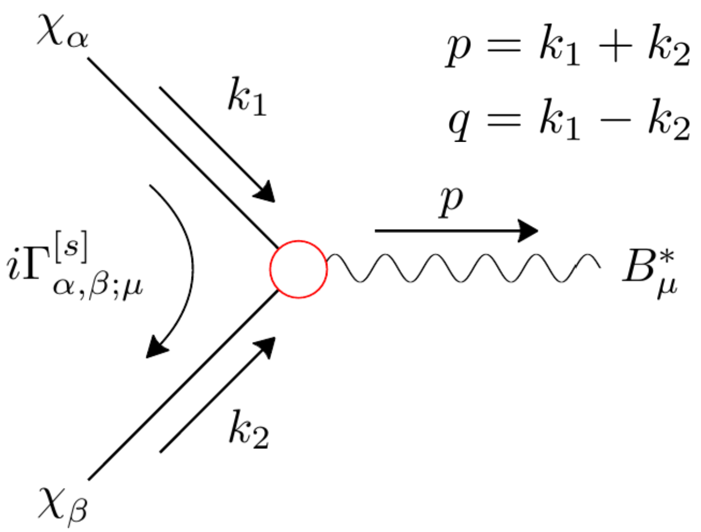
$$n = \begin{cases} s & \text{for bosons} \\ s - 1/2 & \text{for fermions} \end{cases}$$

General anapole vertices for arbitrary spins

[F. Boudjema and C. Hamzaoui, PRD (1991)]

Constructing anapole vertices

[S. Y. Choi and J. H. Jeong, PRD (2022)] ⟶ Γ constructed by collecting basic operators



Integer $s = n \neq 0$ $\quad [\Gamma_B] = [M]$

$$[\Gamma^{[s]}_B] = \sqrt{p^2}\left(\frac{\sqrt{p^2}}{\Lambda}\right)^{2n}\sum_{\tau=1}^{n}\left(b^+_\tau[V^+][S^+]^{\tau-1} + b^-_\tau[V^-][S^-]^{\tau-1}\right)[S^0]^{n-\tau}$$

Half-integer $s = n + 1/2$ $\quad [\Gamma_F] = [1]$

$$[\Gamma^{[s]}_F] = \left(\frac{\sqrt{p^2}}{\Lambda}\right)^{2(n+1)}[A]\left\{f^0[S^0]^n + \sum_{\tau=1}^{n}\left(f^+_\tau[S^+]^\tau + f^-_\tau[S^-]^\tau\right)[S^0]^{n-\tau}\right\}$$

Number of independent terms : $2s$

Normalized momenta

$$\hat{p} = p/\sqrt{p^2}$$
$$\hat{q} = q/\sqrt{-q^2}$$

Conventions

$$g_{\perp\mu\nu} = g_{\mu\nu} - \hat{p}_\mu\hat{p}_\nu + \hat{q}_\mu\hat{q}_\nu$$
$$\gamma_{\perp\mu} = g_{\perp\mu\nu}\gamma^\nu$$
$$\langle\alpha\beta\hat{p}\hat{q}\rangle = \varepsilon_{\alpha\beta\rho\sigma}\,\hat{p}^\rho\hat{q}^\sigma$$

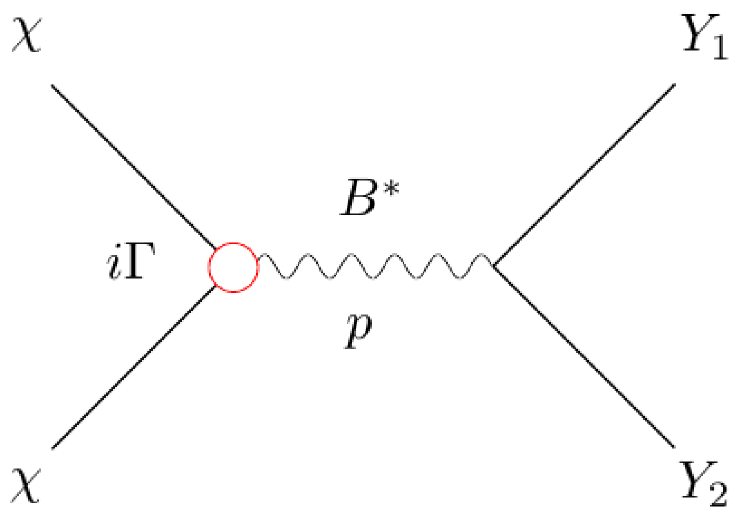
Basic operators

$$S^0_{\alpha\beta} = \hat{p}_\alpha\hat{p}_\beta$$
$$S^\pm_{\alpha\beta} = \left[g_{\perp\alpha\beta} \pm i\langle\alpha\beta\hat{p}\hat{q}\rangle\right]/2$$
$$V^\pm_{\alpha\beta;\mu} = \hat{p}_\beta S^\pm_{\alpha\mu} + \hat{p}_\alpha S^\mp_{\beta\mu}$$
$$A_\mu = \gamma_{\perp\mu}\gamma_5$$

Operator forms

$$S^0_{\alpha_1,\beta_1}\cdots S^0_{\alpha_n\,\beta_n} \to [S^0]^n$$
$$S^\pm_{\alpha_1,\beta_1}\cdots S^\pm_{\alpha_n\,\beta_n} \to [S^\pm]^n$$
$$V^\pm_{\alpha_1,\beta_1;\mu_1}\cdots V^\pm_{\alpha_n,\beta_n;\mu_n} \to [V^\pm]^n$$
$$A_\mu \to [A]$$

Property of anapole vertices



$U(1)$ gauge invariance

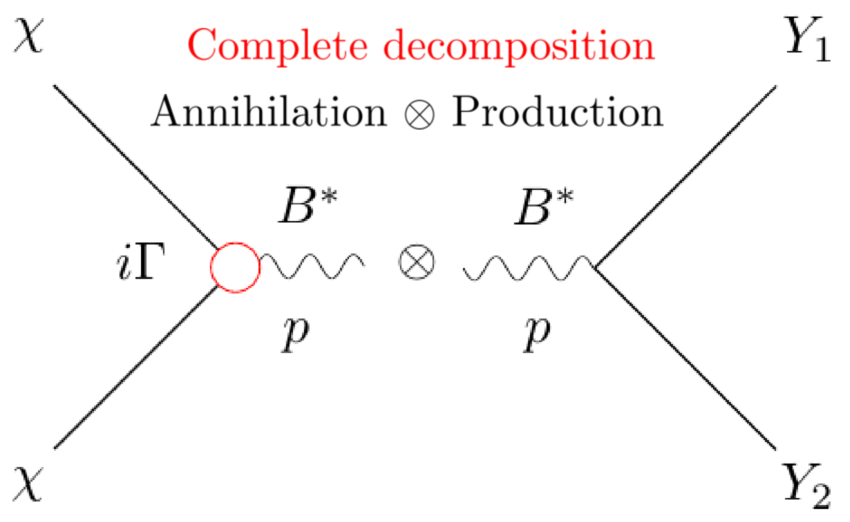
$$p^\mu \Gamma_\mu^{(s)} = 0$$

$$\downarrow$$

$$\rightarrow \quad -g_{\mu\nu} + p_\mu p_\nu / p^2 \quad \longrightarrow$$

$$= \sum_\sigma \varepsilon^{*\mu}(p,\sigma)\varepsilon^\nu(p,\sigma)$$

$\oplus$ IP relation



$$\mathcal{M}(\phi,\theta) = \mathcal{X}_{\lambda_1,\lambda_2}\mathcal{Y}_{\sigma_1,\sigma_2} D^{1*}_{\lambda_1-\lambda_2,\sigma_1-\sigma_2}(\phi,\theta,0)$$

with $|\lambda_1 - \lambda_2|, |\sigma_1 - \sigma_2| \leq 1$

Identical particle relation

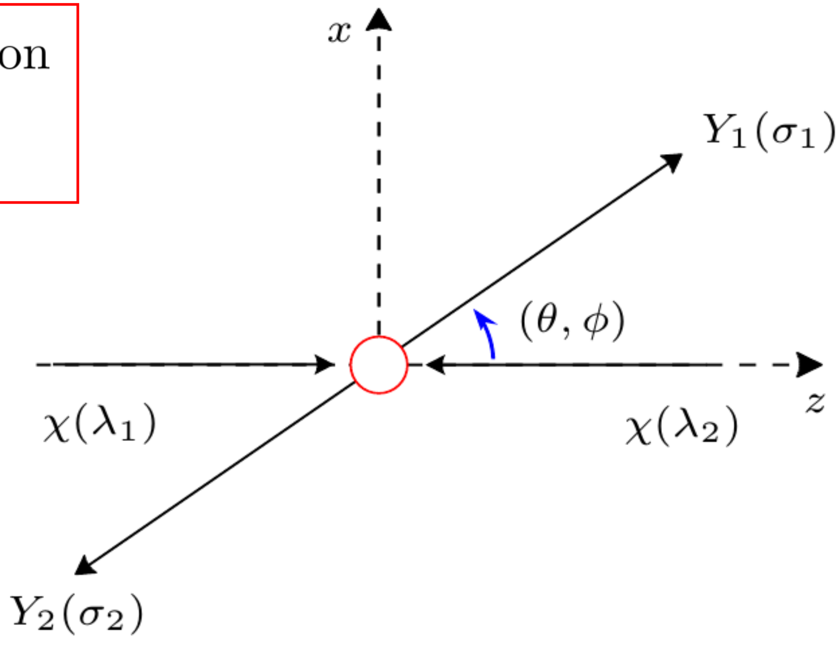
$$\mathcal{X}_{\lambda_1,\lambda_2} = -\mathcal{X}_{\lambda_2,\lambda_1}$$

$\longrightarrow \quad \lambda_1 - \lambda_2 \neq 0$

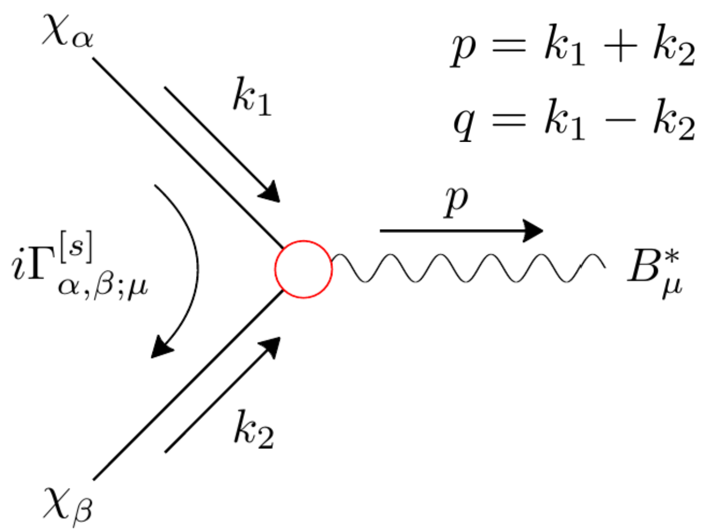
Annihilation — Production

$$\overline{\sum}|\mathcal{M}|^2 = \frac{1}{2}\sum_\lambda |\mathcal{X}_{\lambda,\lambda-1}|^2 \Big[\Sigma_T + \Sigma_L + (\Sigma_T - \Sigma_L)\cos^2\theta\Big]$$

$$\Sigma_T = \frac{1}{2}\overline{\sum_\sigma}\Big[|\mathcal{Y}_{\sigma,\sigma-1}|^2 + |\mathcal{Y}_{\sigma-1,\sigma}|^2\Big], \quad \Sigma_L = \overline{\sum_\sigma}|\mathcal{Y}_{\sigma,\sigma}|^2$$



Constructing anapole vertices



$$\Gamma^{[1/2]}_{\mu} \overset{\text{eff}}{=} \frac{a_{1/2}}{\Lambda^2} p^2 \gamma_{\perp\mu}\gamma_5$$

$$\Gamma^{[1]}_{\alpha,\beta;\mu} \overset{\text{eff}}{=} \frac{ip^2}{\Lambda^2}\left[a_1 \langle \alpha\beta\mu q\rangle_\perp - b_1 \left(p_\alpha g_{\perp\beta\mu} + p_\beta g_{\perp\alpha\mu}\right)\right]$$

↓

$$\mathcal{L}_{1/2} = \frac{a_{1/2}}{2\Lambda^2}\bar{\chi}\gamma^\mu\gamma_5\chi\,\partial_\nu B^{\mu\nu}$$

$$\mathcal{L}_1 = \left[\frac{a_1}{2\Lambda^2}\varepsilon_{\alpha\beta\mu\rho}\left[\chi^\alpha(\partial^\rho\chi^\beta) - (\partial^\rho\chi^\alpha)\chi^\beta\right] + \frac{b_1}{2\Lambda^2}\partial^\rho(\chi_\rho\chi_\mu + \chi_\mu\chi_\rho)\right]\partial_\nu B^{\mu\nu}$$

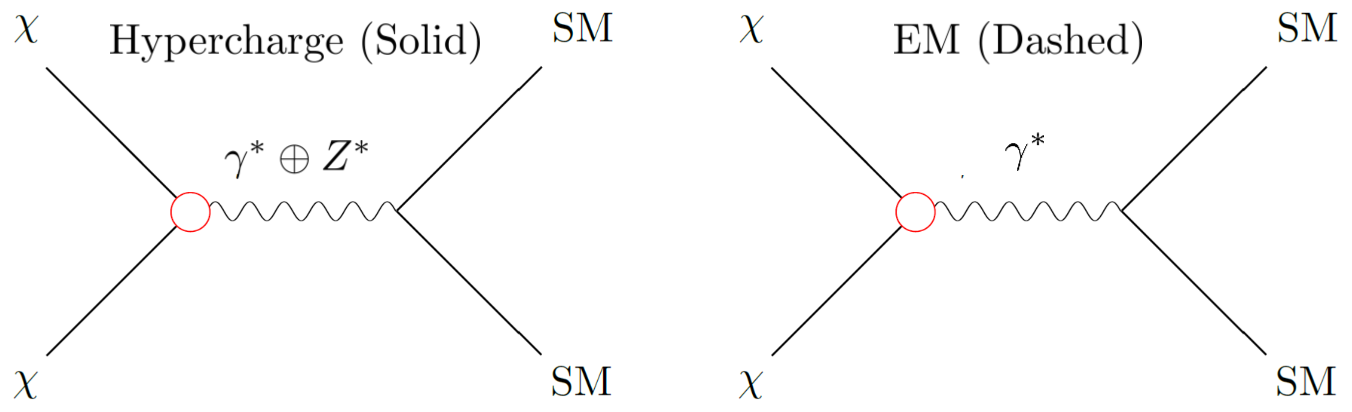
In the non-relativistic limit

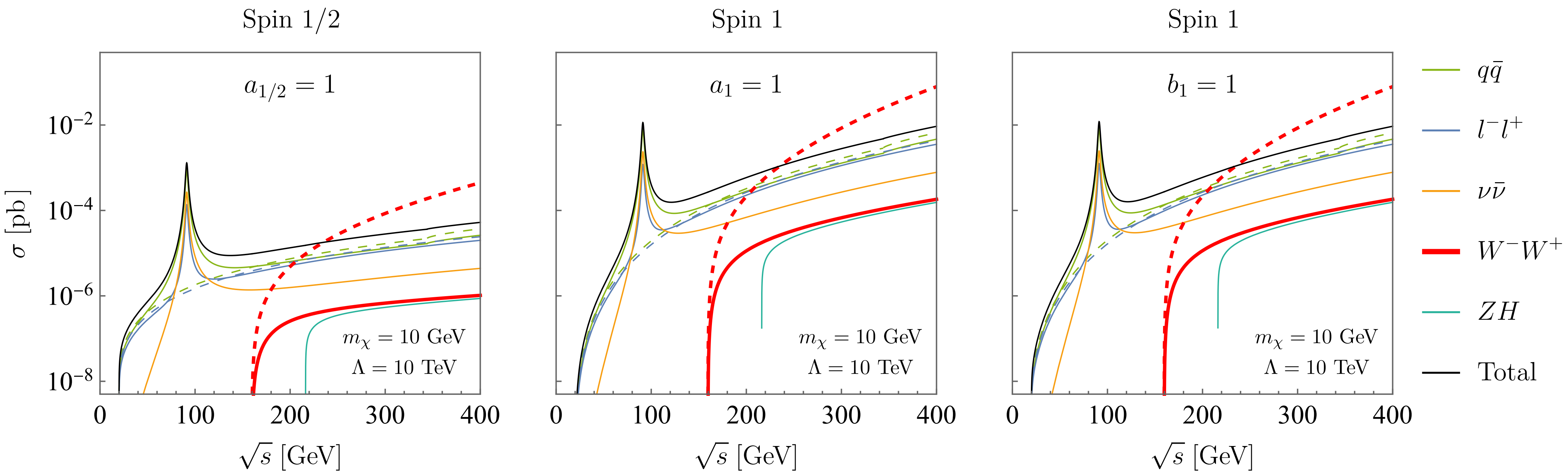
$$a_{1/2} \;\&\; a_1 \;\rightarrow\; \mathcal{H} \propto -\frac{\vec{\mathbf{S}}}{S}\cdot\vec{j}_{\text{ext}} \quad \text{(Dipole [Odd-parity])}$$

$$b_1 \;\rightarrow\; \mathcal{H} \propto \frac{3}{2S(2S-1)}\left[\mathbf{S}^l\mathbf{S}^m + \mathbf{S}^l\mathbf{S}^m - \frac{2}{3}\delta^{ij}S(S+1)\right]\nabla^l j^m_{\text{ext}} \quad \text{(Quadrupole [Even-parity])}$$

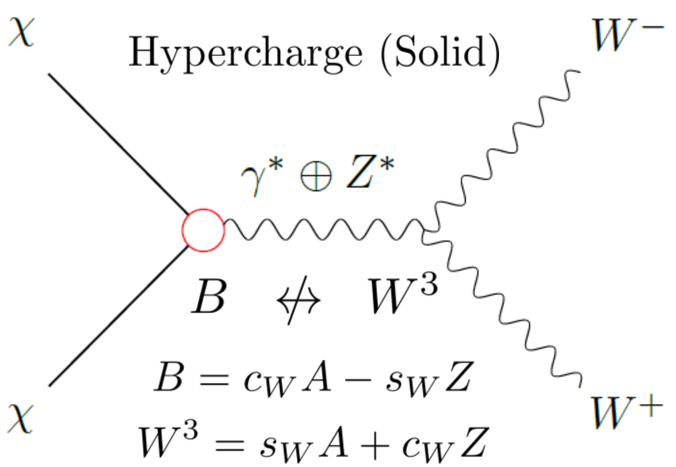
U(1) gauge boson → Hypercharge gauge boson $B^\mu = c_W A^\mu - s_W Z^\mu$

Hypercharge vs EM





Hypercharge vs EM

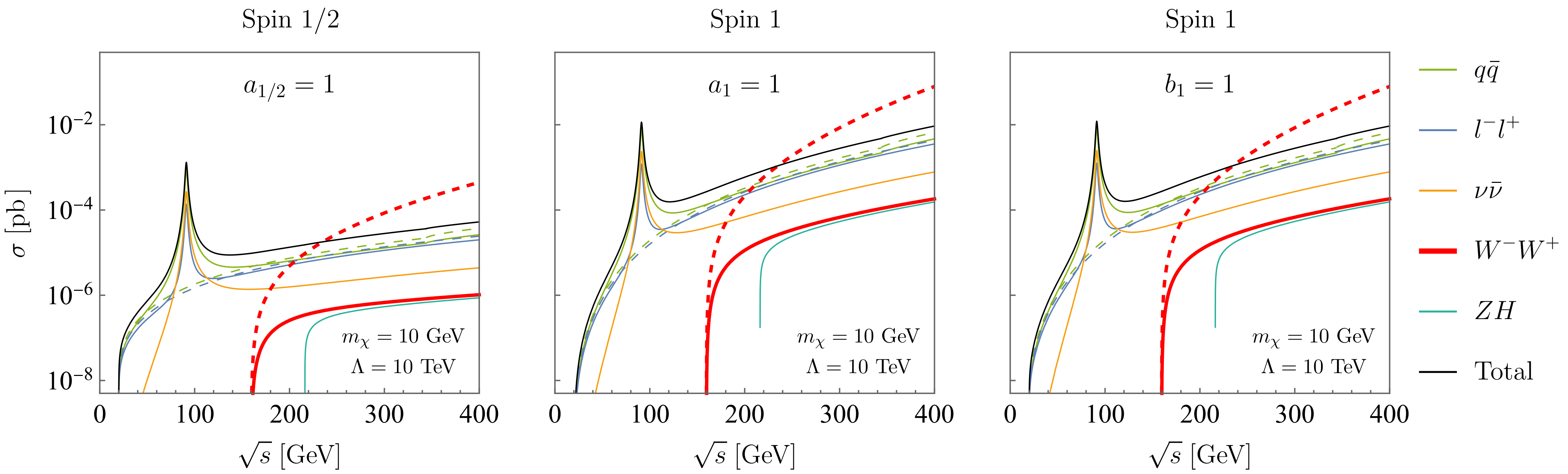


$\sqrt{s}$ ↑

$B \nleftrightarrow W^3$

restored $\mathrm{U}(1)_Y$ symmetry → Improved unitarity properties

$\gamma \oplus Z$



Constraints from the relic abundance [P. Gondolo and G. Gelmini, NPB (1991)]

$$\sigma_{1/2}^{[\chi\chi\to \mathrm{SMSM}]} = \frac{1}{4}\cdot\frac{|a_{1/2}|^2}{\Lambda^4}\cdot\beta_\chi \Sigma^{\mathrm{SM}}$$

p wave

$$\sigma_{1}^{[\chi\chi\to \mathrm{SMSM}]} = \frac{1}{9}\cdot\left[\frac{|a_1|^2\,\beta_\chi^2 + |b_1|^2}{\Lambda^4}\right]\left(\frac{s}{4m_\chi^2}\right)\cdot\beta_\chi \Sigma^{\mathrm{SM}}$$

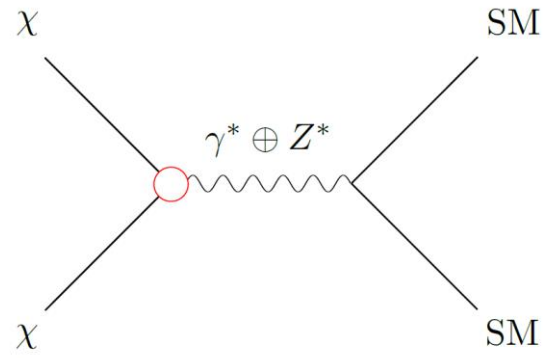
d wave p wave

In the c.m.

β_χ : χ speed

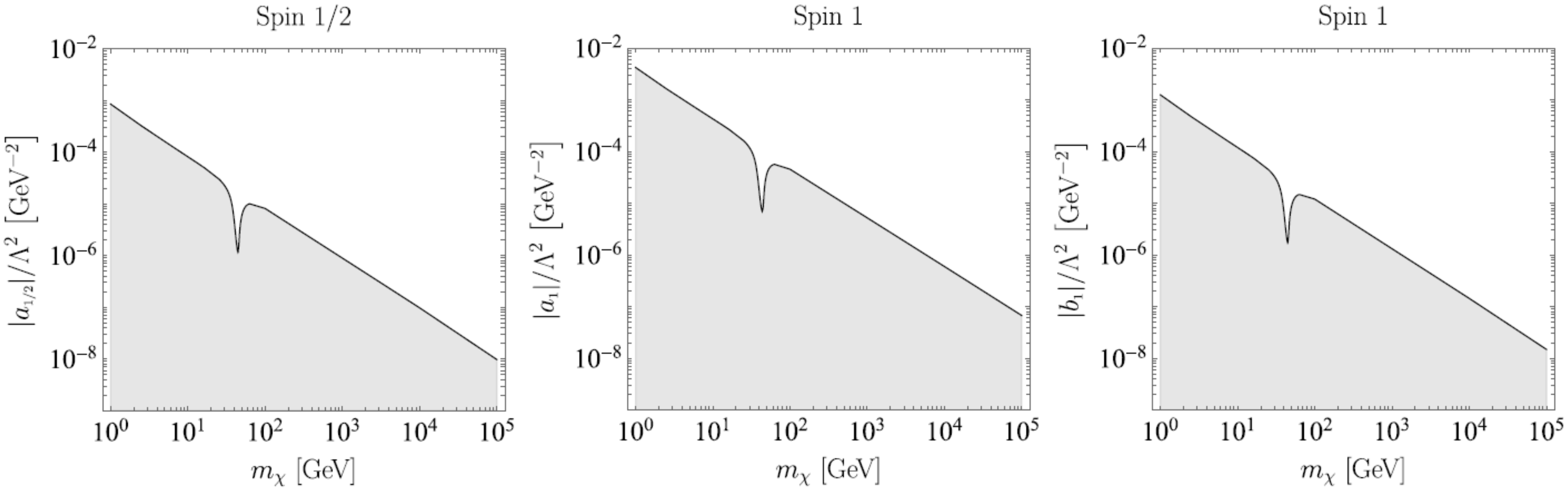
$\sqrt{s}$: Annihilation energy

Annihilation processes



$\frac{1}{4}\to\frac{1}{9} \Rightarrow$ stronger constraints on the spin-1 case

$\beta_\chi^2 \Rightarrow$ much stronger constraints on $|a_1|$



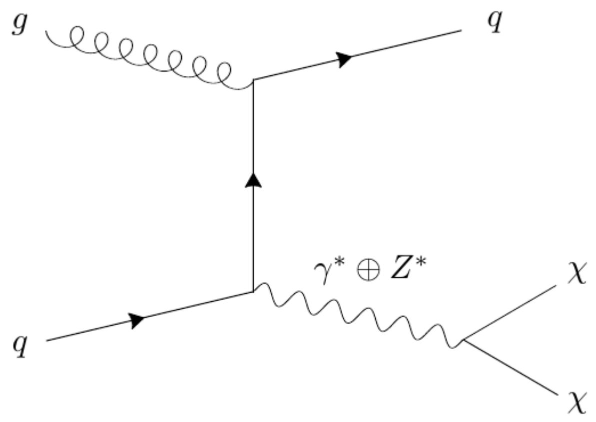
Constraints from the mono-jet searches at the LHC [G. Aad *et al.* [ATLAS], PRD (2021)]

$$\sigma_{1/2}^{[gq\to q\chi\chi]} \propto \frac{|a_{1/2}|^2}{\Lambda^4}$$

$$\sigma_{1}^{[gq\to q\chi\chi]} \propto \left[\frac{|a_1|^2\,\beta_\chi^2 + |b_1|^2}{\Lambda^4}\right]\left(\frac{Q^2}{4m_\chi^2}\right)$$

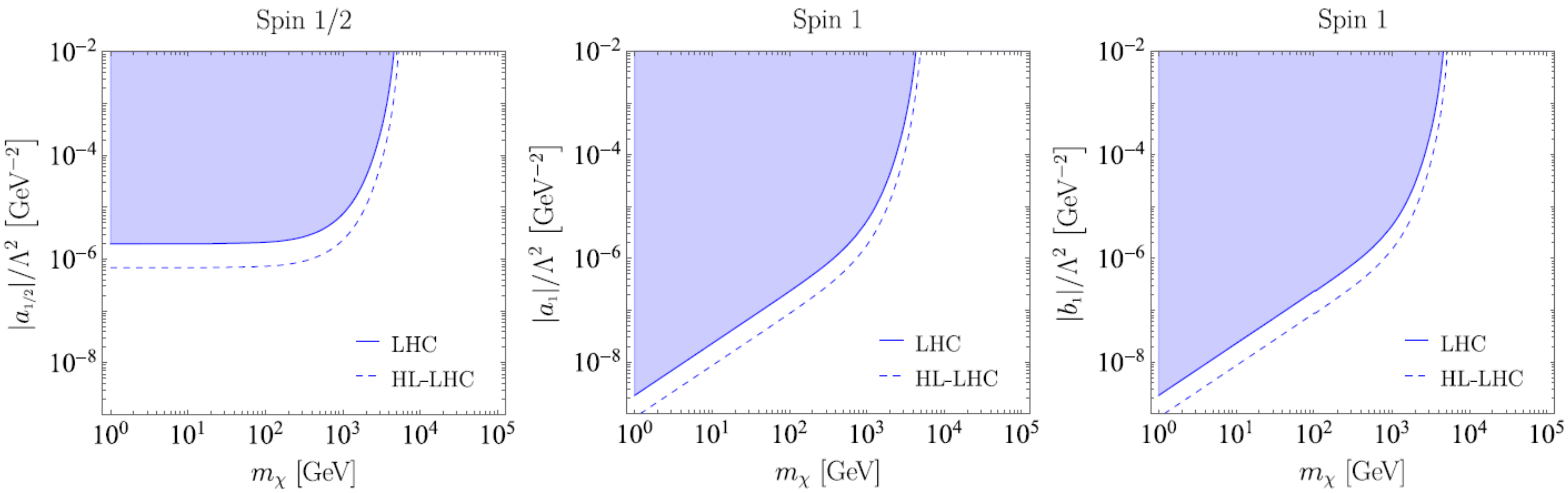
Q^2 : Invariant mass of γ^* and Z^*

Monojet processes



longitudinal ⇒ stronger (HL-)LHC constraints on the spin-1 case

$\beta_\chi \approx 1$ ⇒ similar constraints on the spin-1 couplings $|a_1|$ and $|b_1|$



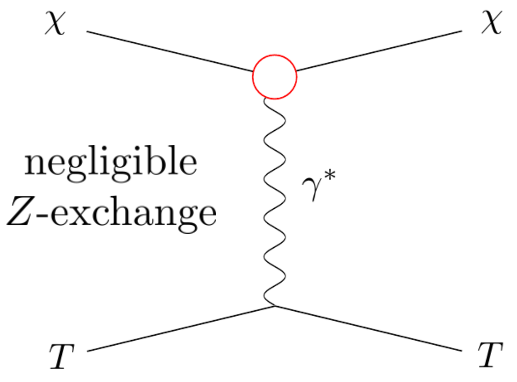
Constraints from the DM direct detection XENONnT [J. Hisano, A. Ibarra and R. Nagai, JCAP (2020)]

$$\frac{d\sigma_{1/2}^{[\chi T \to \chi T]}}{dE_R} \propto \frac{1}{2} \cdot \frac{|a_{1/2}|^2}{\Lambda^4}$$

$$\frac{d\sigma_{1}^{[\chi T \to \chi T]}}{dE_R} \propto \frac{1}{3} \cdot \left[|a_1|^2 \left(1 + \frac{m_T E_R}{2m_\chi^2} \right) + |b_1|^2 \frac{m_T E_R}{2m_\chi^2} \right]$$

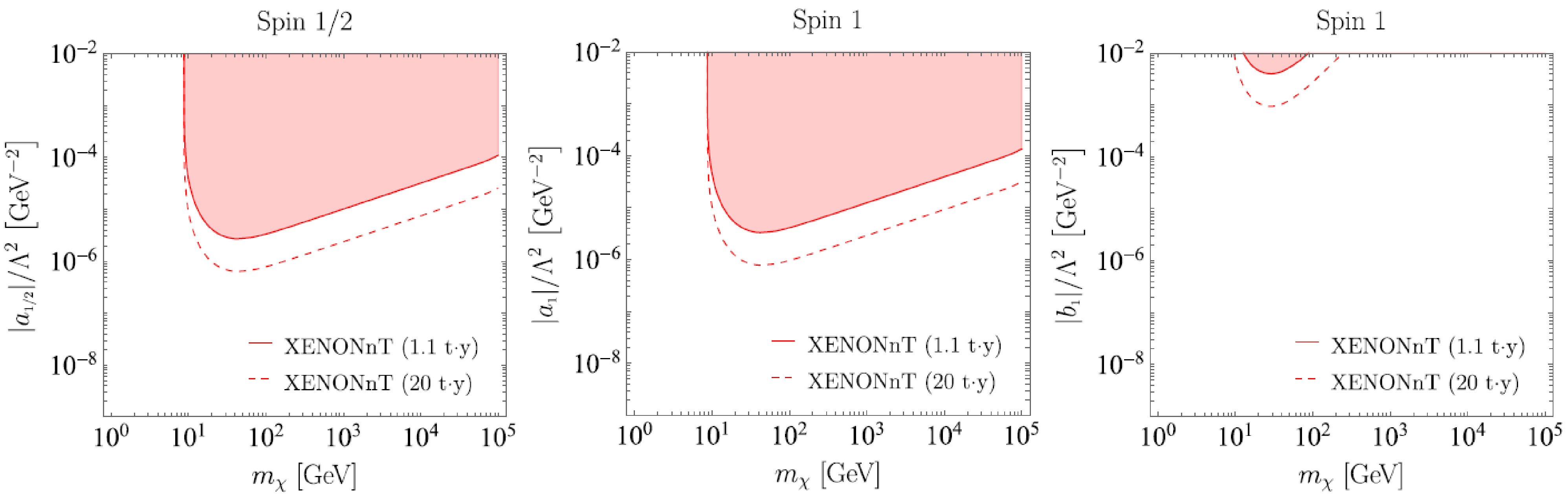
E_R : Recoil energy ($E_R << m_\chi$)

Scattering processes

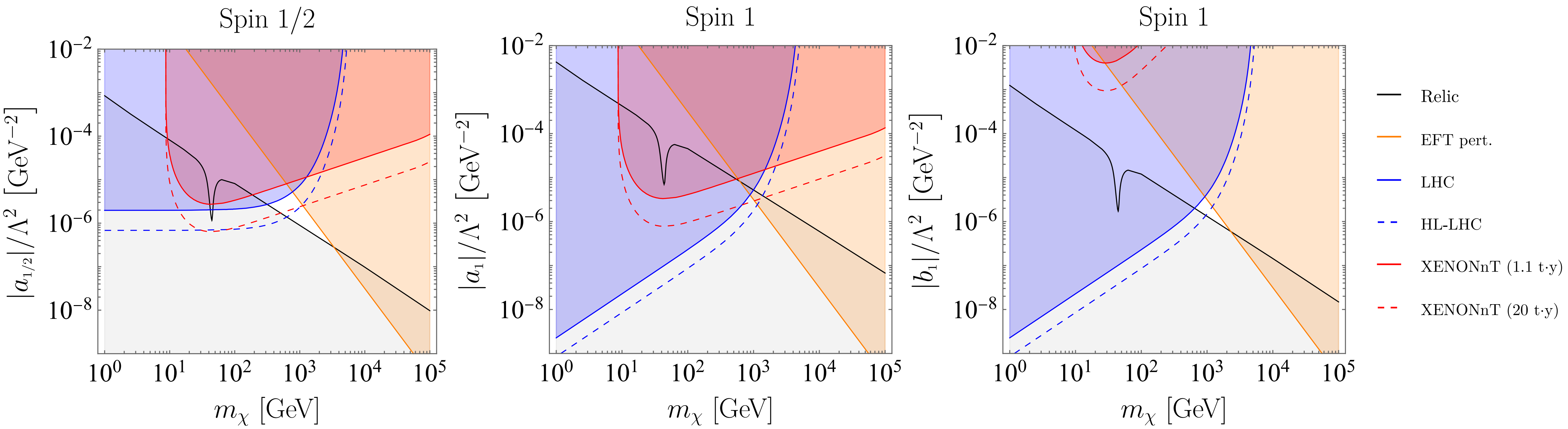


T: Target nucleus (Xe)

extremely small $m_T E_R/(2m_\chi^2) \Rightarrow$ very weak constraint on $|b_1|$



Combined constraints with the naive EFT perterbativity bound



Naive EFT perterbativity bound

$$\frac{C}{\Lambda^2} s \leq 4\pi \quad \rightarrow \quad \frac{C}{\Lambda^2} 4 m_\chi^2 \leq 4\pi$$

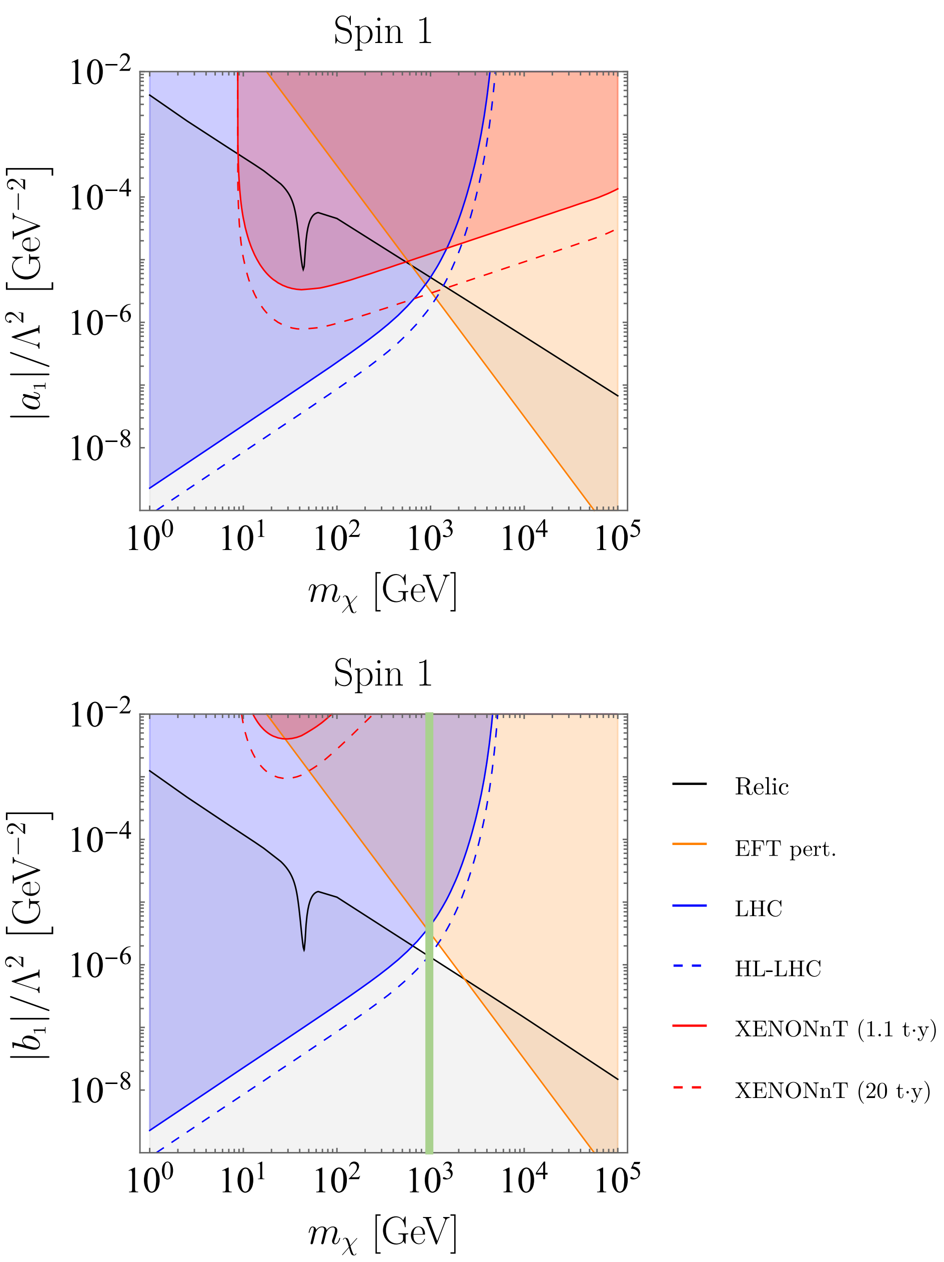
$$\left(C = |a_{1/2}| \text{ or } \sqrt{|a_1|^2 + |b_1|^2} \right)$$

Features

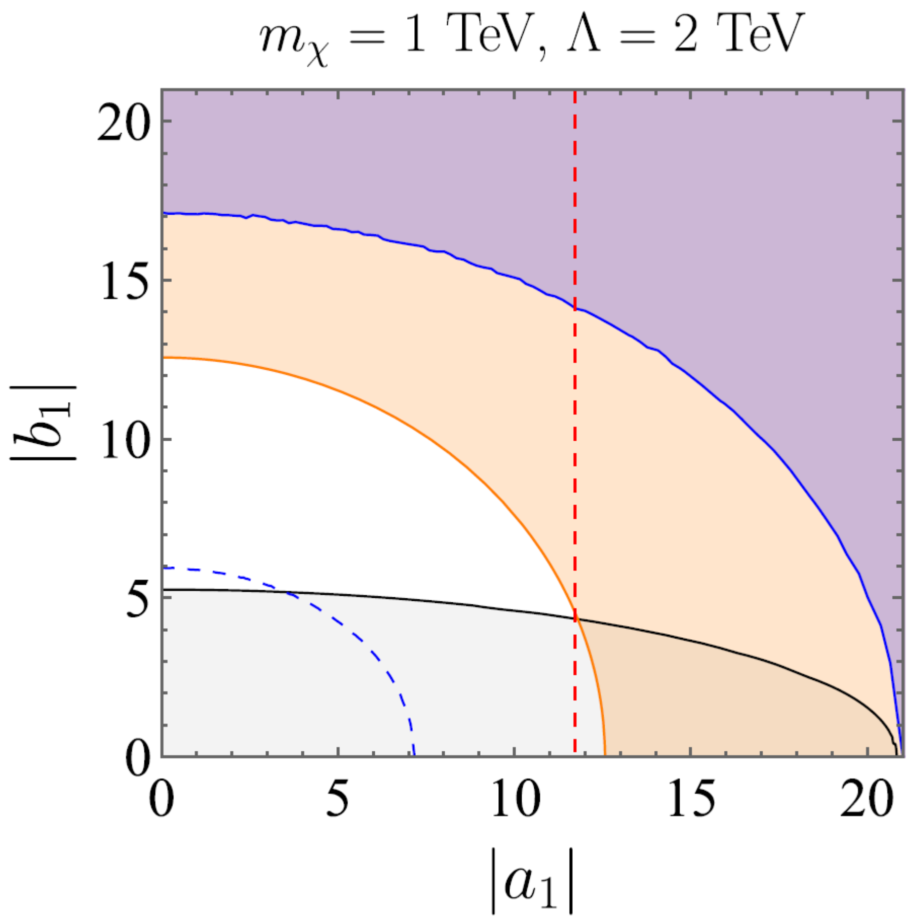
- ✓ Stronger constraints for the spin-1 case than the spin-1/2 case
- ✓ The spin-1 case with $|a_1|$ (middle) is already completely excluded
- ✓ Promising XENONnT (20 t· y) and HL-LHC especially for the spin-1/2 case

[O. Brüning and M. Zerlauth, JACoW (2023), TUYG1]
[J.Aalbersetal et al., J.Phys (2023)]

Correlated a_1 and b_1 constraints



$$\sigma_1 \propto \left[\frac{|a_1|^2\, \beta_\chi^2 + |b_1|^2}{\Lambda^4}\right]\left(\frac{s}{4m_\chi^2}\right) \quad \rightarrow \quad \text{Ellipses}$$



Conclusion

1. General 3-point anapole vertices were constructed in a compact form for systematic analytic analyses and other projects for any spin

2. Detailed analytic and numerical analyses were performed for the spin-1/2 and 1 hypercharge anapole DM particles

3. Nearly half of the allowed region for the spin-1/2 case excluded by the future XENONnT experiments in 5 years at a faster pace than the HL-LHC

4. Nearly half of the allowed region for the spin-1 case excluded by the full running of the HL-LHC

5. Stronger constraints on the spin-1 case than the spin-1/2 case

6. Complete exclusion of the higher-spin anapole DM
   (stronger relic-abundance $\oplus$ LHC constraints)

7. Finding UV scenarios of the hypercharge anapole DM