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Characterizing the hypercharge anapole dark matter particle

in progress

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Motivation

Conventional DM candidate: Weakly interacting massive particles (WIMPs)

Electrically neutral, colorless $\rightarrow$ Majorana (Self-conjugate) particle $\rightarrow$ (SUSY, UED, $\cdots$)

[S. P. Martin, Adv. Ser. Direct. High Energy Phys. (1998)],
[A. Perez-Lorenzana, J. Phys. Conf. Ser. (2005)], $\cdots$

A Majorana particle coupled to a U(1) gauge boson $\rightarrow$ Anapole interaction

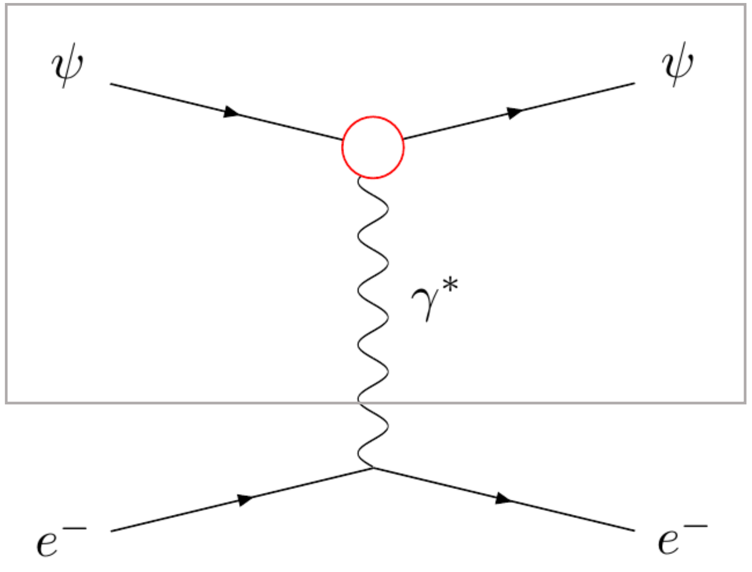
Ex) EM anapole interaction

General effective EM Lagrangian for spin 1/2

$$\mathcal{L}^{\psi}_{EM} = e\,\bar{\psi}\gamma^{\mu}\psi A_{\mu} + a\,\bar{\psi}\gamma^{\mu}\gamma_5\psi\,\partial_{\nu}F^{\mu\nu} + \mu\, i\,\bar{\psi}\sigma^{\mu\nu}\gamma_5\psi\,F^{\mu\nu} + d\, i\,\bar{\psi}\sigma^{\mu\nu}\psi\,F^{\mu\nu}$$

$$\rightarrow \quad H_{EM} = -e\,\phi_{\rm ext} - \boxed{a\,\hat{S}\cdot\vec{j}_{\rm ext}} - \mu\,\hat{S}\cdot\vec{B}_{\rm ext} - d\,\hat{S}\cdot\vec{E}_{\rm ext}$$

Interaction direct with external current $\rightarrow$ Contact interaction



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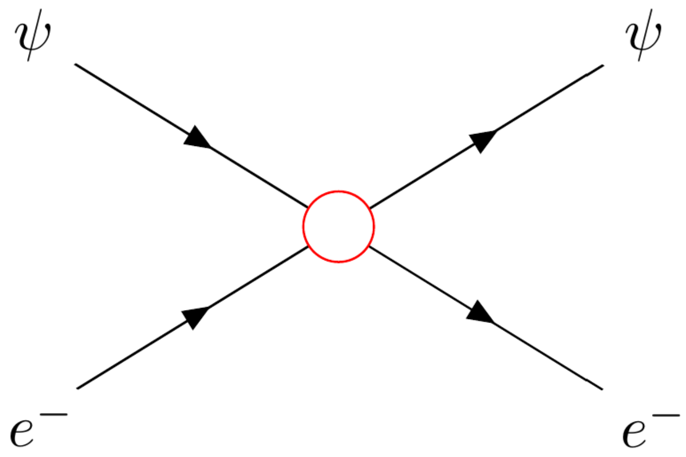

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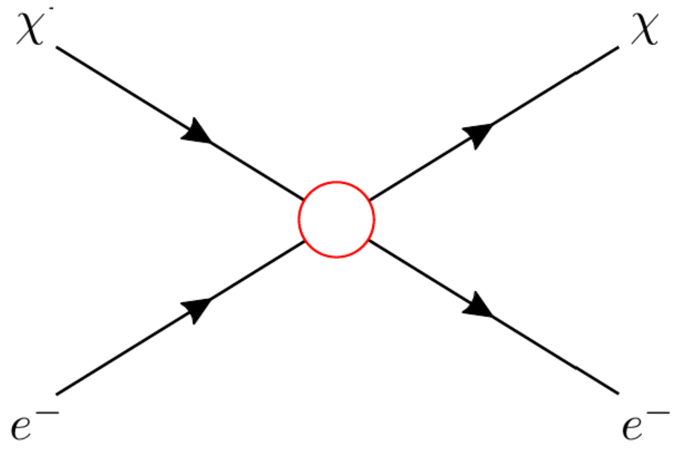
Interaction direct with external current → Contact interaction

$$\left(\begin{array}{l}\psi\text{: Dirac}\\ \chi\text{: Majorana}\end{array}\right) \quad \rightarrow \quad \mathcal{L}^{\chi}_{EM} = a\,\bar{\chi}\gamma^{\mu}\gamma_5\chi\,\partial_{\nu}F^{\mu\nu}$$



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Studies including anapole DM

	Spin-1/2 EM anapole	Spin-1 EM anapole	Spin-1/2 hypercharge anapole
Relic density	[C. M. Ho and R. J. Scherrer, PLB (2013)] $\cdots$		Partial restoration of $\sigma[\chi\chi \leftrightarrow W^-W^+]$ divergence at high-energy limits [C. Arina, A. Cheek, K. Mimasu and L. Pagani, EPJC (2021)]
Direc detection	[M. Pospelov and T. ter Veldhuis, PLB (2000)] $\cdots$	[J. Hisano, A. Ibarra and R. Nagai, JCAP (2020)] $\cdots$	
Collider	[Y. Gao, C. M. Ho and R. J. Scherrer, PRD (2014)] $\cdots$		
Indirect detection	[C. M. Ho and R. J. Scherrer, PRD (2013)] $\cdots$		
UV completion	[L. G. Cabral-Rosetti, M. Mondragón and E. Reyes-Pérez, NPB (2016)] $\cdots$		

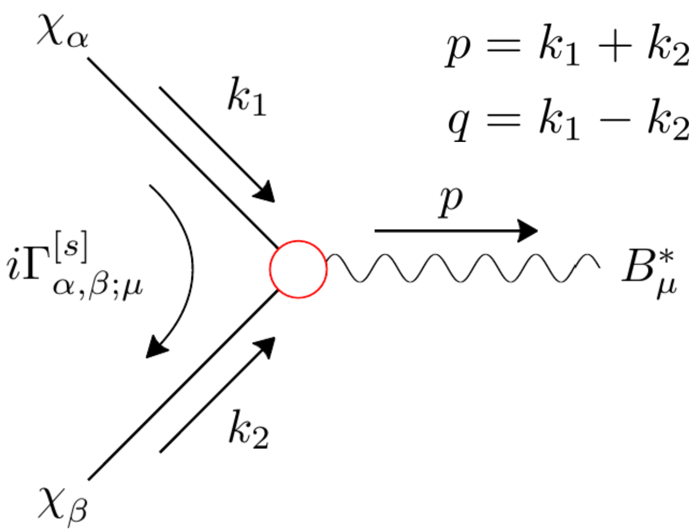
Characterizing the hypercharge anapole DM particle

[Spin 1/2, 1, $\cdots$]

Outline

1. Anapole vertices
2. Exclusion limits on the hypercharge anapole DM of spin-1/2 and -1
   (a) DM relic density
   (b) Collider searches
   (c) Direct searches
   + Naive perturbativity bound
3. Conclusion

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

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

$$\alpha \equiv \alpha_1 \cdots \alpha_n$$
$$\beta \equiv \beta_1 \cdots \beta_n$$

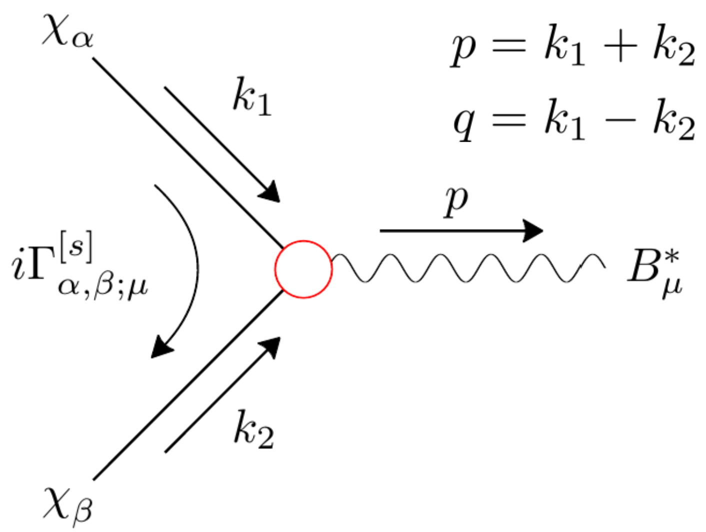
General anapole vertices for arbitrary spins

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

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

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

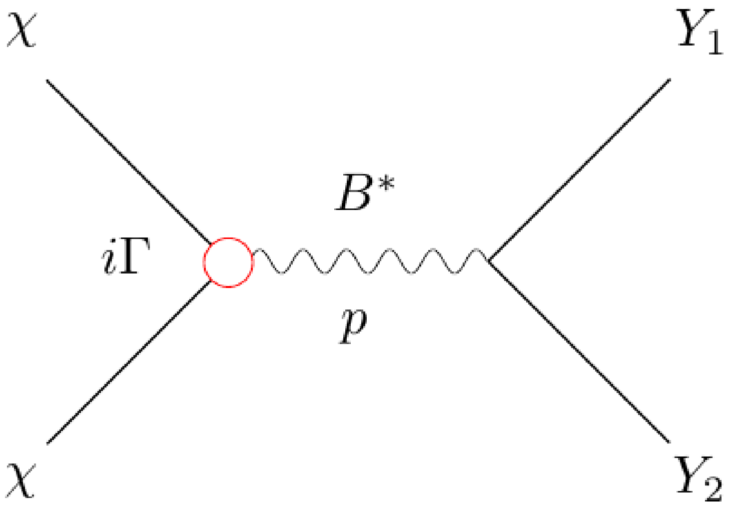
$$\hat{p} = p/\sqrt{p^2}$$
$$\hat{q} = q/\sqrt{-q^2}$$

Conventions

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

Operator forms			Basic operators
$S^0_{\alpha_1,\beta_1}\cdots S^0_{\alpha_n\,\beta_n}$	$\to$	$[S^0]^n$	$S^0_{\alpha\beta} = \hat{p}_\alpha\hat{p}_\beta$
$S^\pm_{\alpha_1,\beta_1}\cdots S^\pm_{\alpha_n\,\beta_n}$	$\to$	$[S^\pm]^n$	$S^\pm_{\alpha\beta} = \left[g_{\perp\alpha\beta} \pm i\langle\alpha\beta\hat{p}\hat{q}\rangle\right]/2$
$V^\pm_{\alpha_1,\beta_1;\mu_1}\cdots V^\pm_{\alpha_n,\beta_n;\mu_n}$	$\to$	$[V^\pm]^n$	$V^\pm_{\alpha\beta;\mu} = \hat{p}_\beta S^\pm_{\alpha\mu} + \hat{p}_\alpha S^\mp_{\beta\mu}$
A_μ	$\to$	$[A]$	$A_\mu = \gamma_{\perp\mu}\gamma_5$

Properties of anapole interaction



$U(1)$ gauge invariance

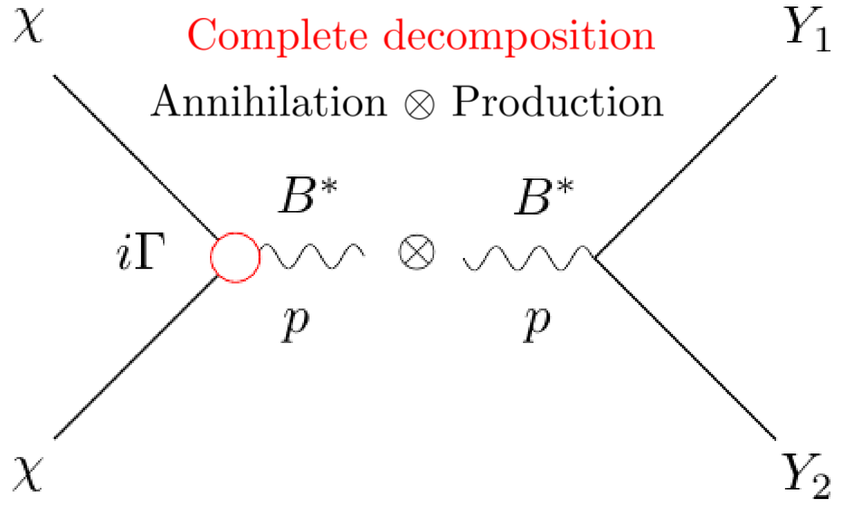
$$p^\mu \Gamma^{(s)}_\mu = 0$$

$$\downarrow$$

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

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

$\oplus$ 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

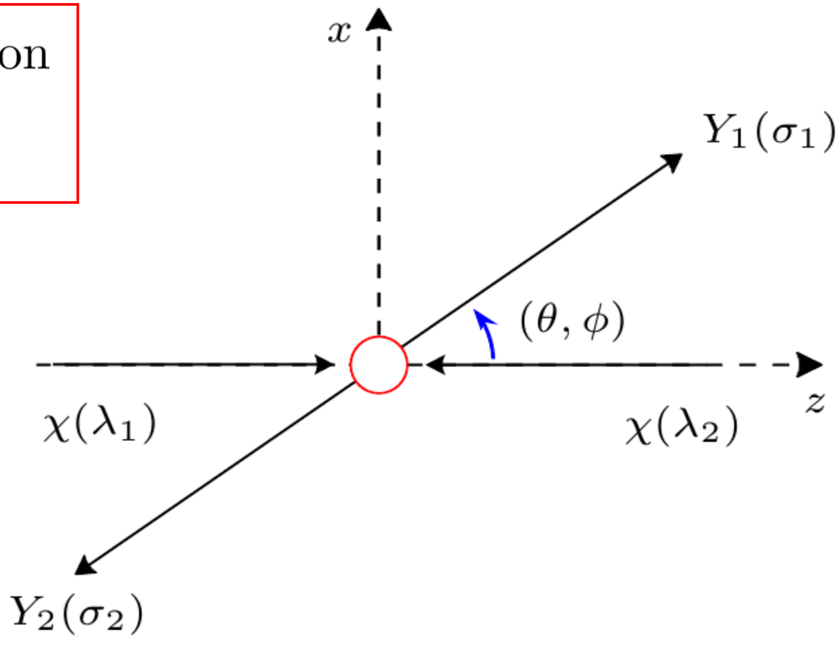
$$\mathcal{X}_{\lambda_1,\lambda_2} = -\mathcal{X}_{\lambda_2,\lambda_1}$$

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

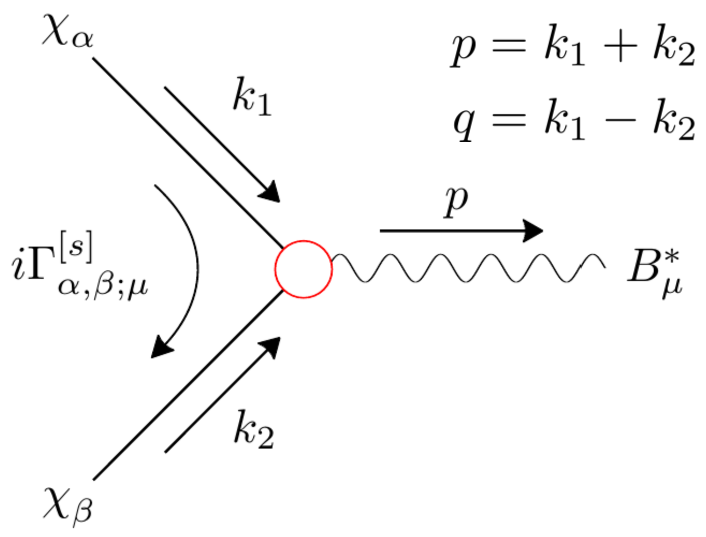
Annihilation — Production

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

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



Vertices and Lagrangian for spins 1/2 and 1



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

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

$$\downarrow$$

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

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

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

Coupling constraints imposed by the relic density

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

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

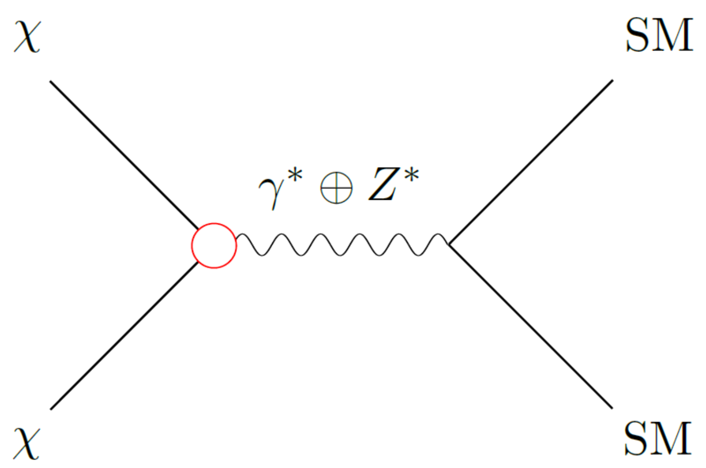
→ Strong constraint

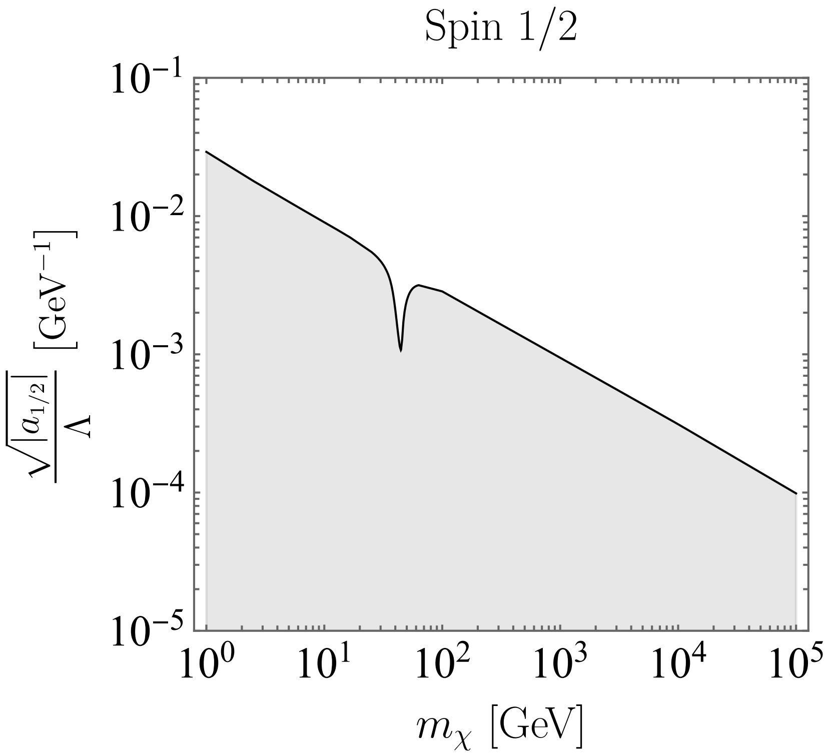
At the c.m.

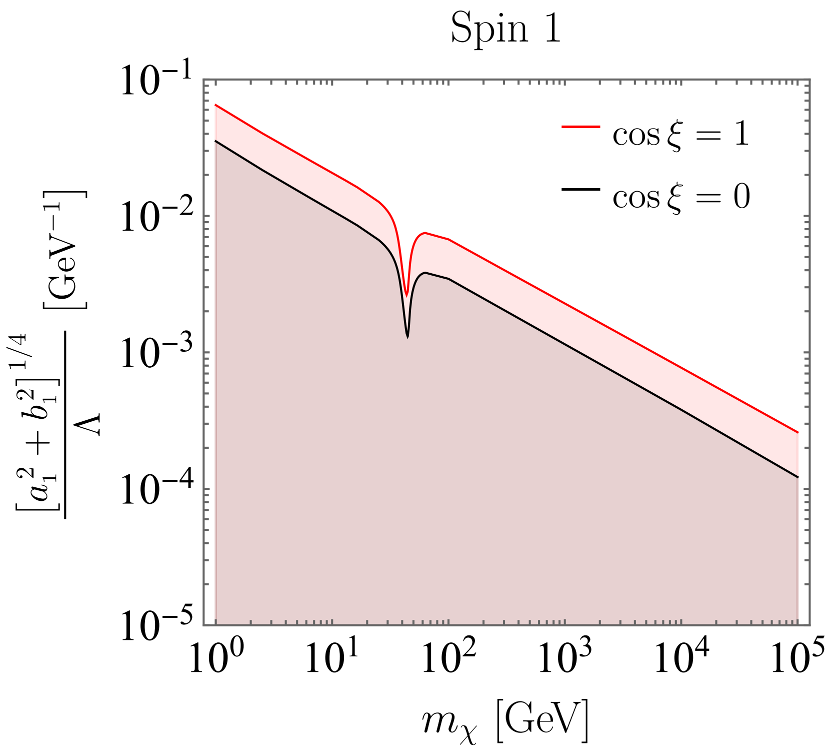
β_χ : χ speed

$\sqrt{s}$: Annihilation energy

Annihilation processes







$$\cos\xi = \frac{a_1}{\sqrt{a_1^2+b_1^2}}$$

$$\sin\xi = \frac{b_1}{\sqrt{a_1^2+b_1^2}}$$

[P. Gondolo and G. Gelmini, NPB (1991)]

Coupling constraints imposed by the collider (LHC)

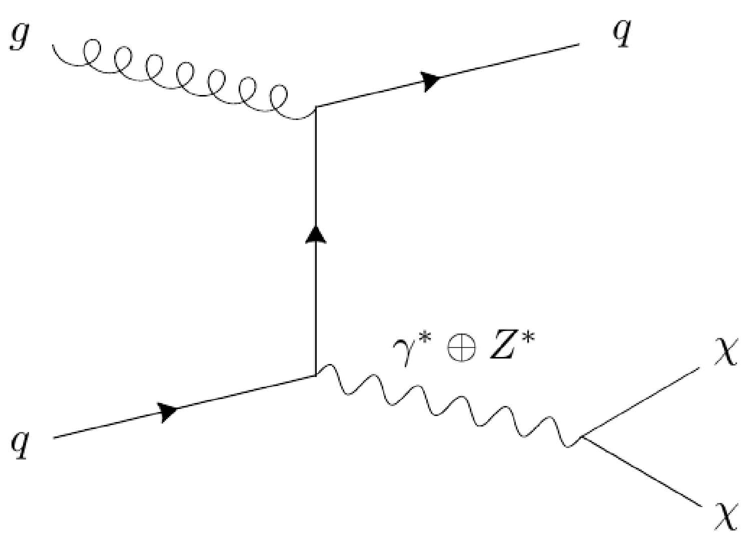
$$\sigma_{1/2}^{[gq\to q\chi\chi]} \propto \frac{a_{1/2}^2}{\Lambda^4}$$

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

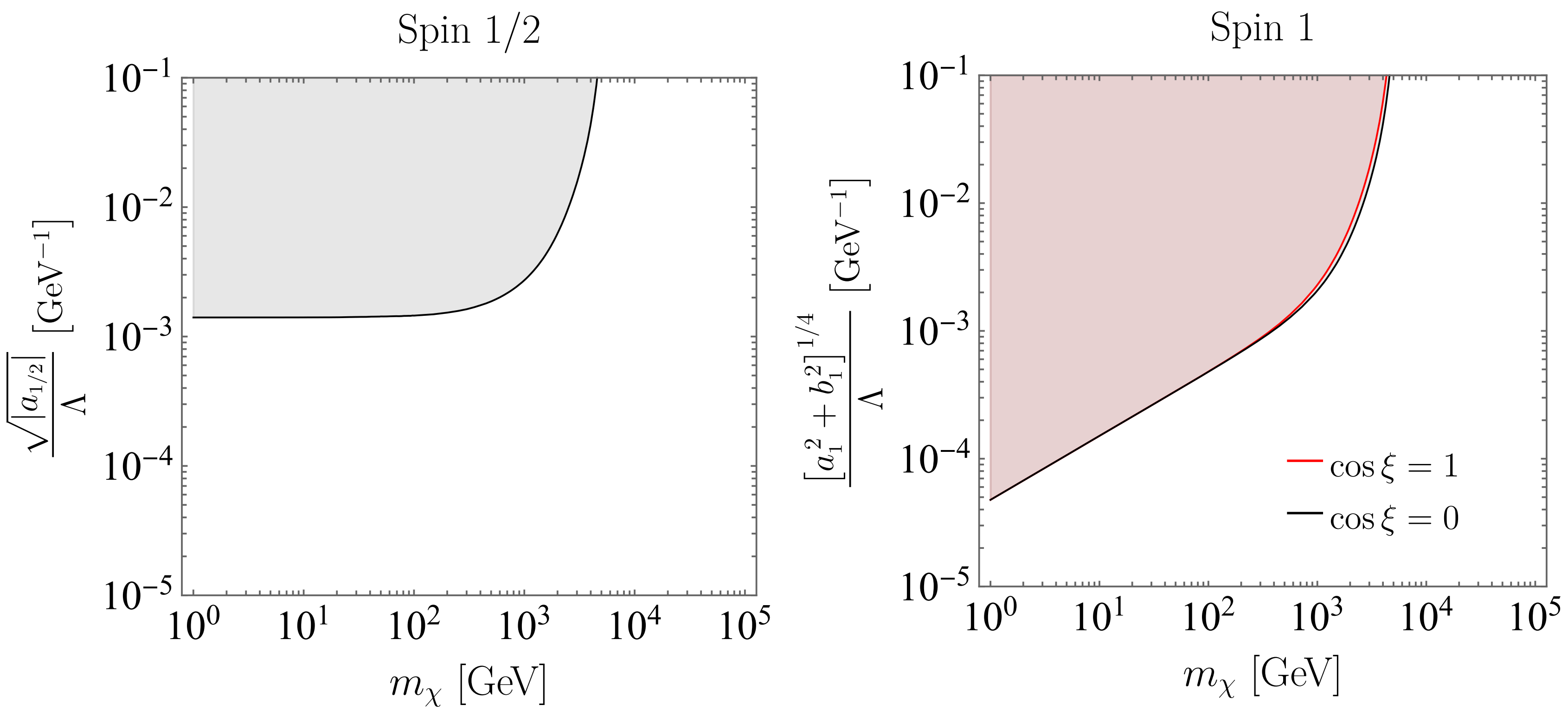
Q^2 : Invariant mass of γ^* and Z^*

Longitudinal components $\rightarrow$ Strong constraints

Monojet processes



$\sqrt{s} = 13$ TeV



$$\cos\xi = \frac{a_1}{\sqrt{a_1^2 + b_1^2}}$$

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[G. Aad *et al.* [ATLAS], PRD (2021)]

Coupling constraints imposed by the direct detection (XENONnT)

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

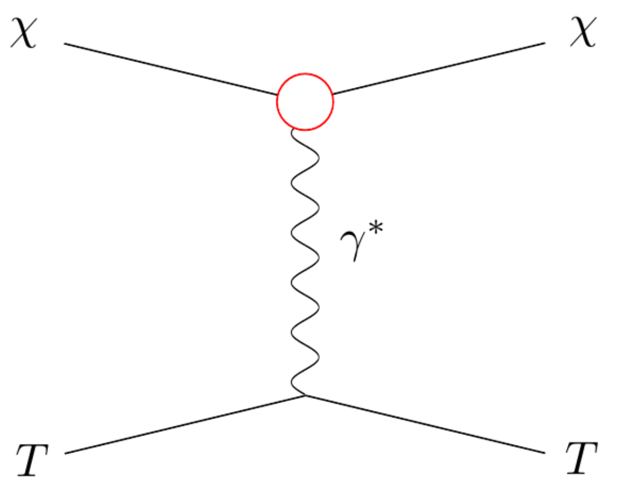
$$\frac{d\sigma_{1}^{[\chi T \to \chi T]}}{dE_R} \propto \frac{1}{3} \cdot \left[a_1^2 \left(1 + \frac{m_T E_R}{2 m_\chi^2} \right) + b_1^2 \frac{m_T E_R}{2 m_\chi^2} \right]$$

Proportional to E_R

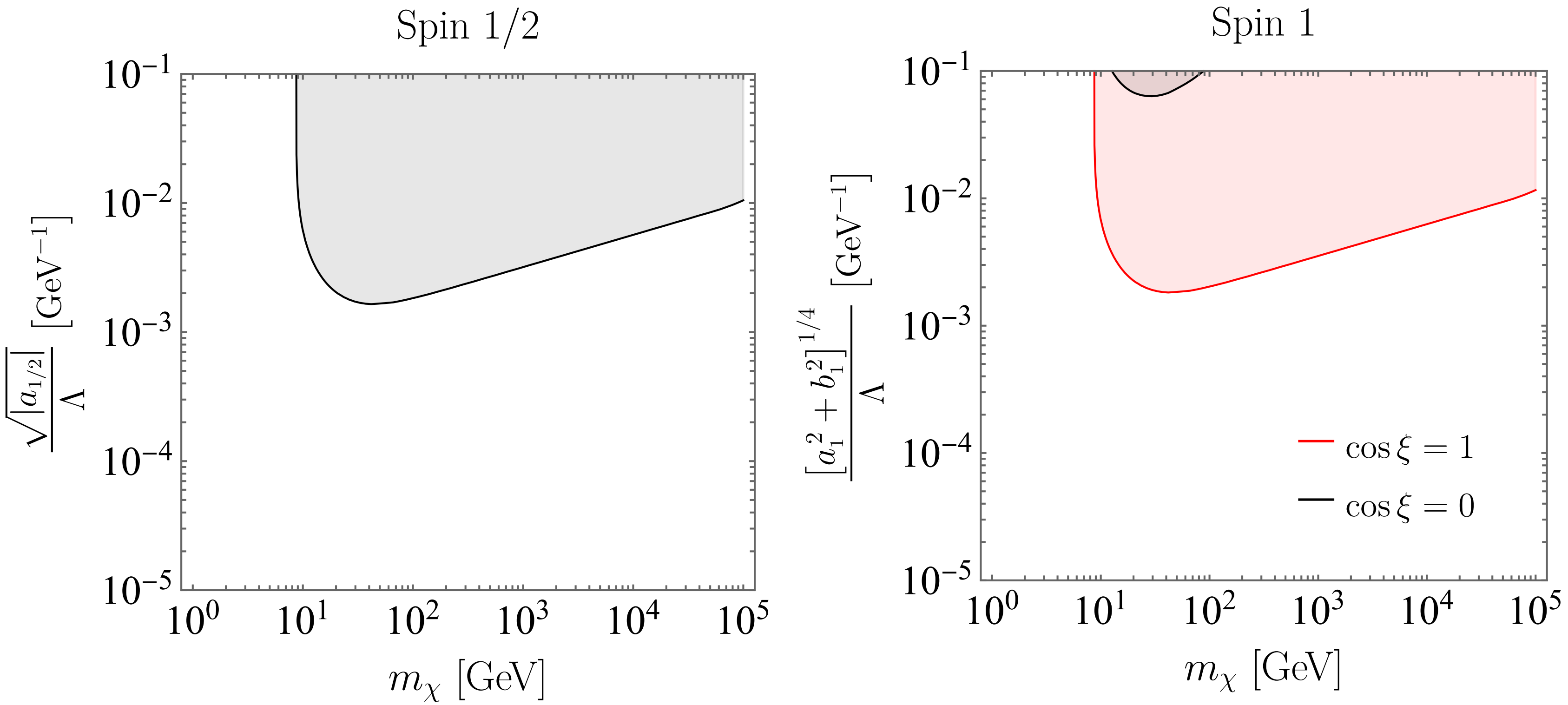
$\rightarrow$ Weak constraint

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

Scattering processes



T: Target nucleus (Xe)



$$\cos\xi = \frac{a_1}{\sqrt{a_1^2 + b_1^2}}$$

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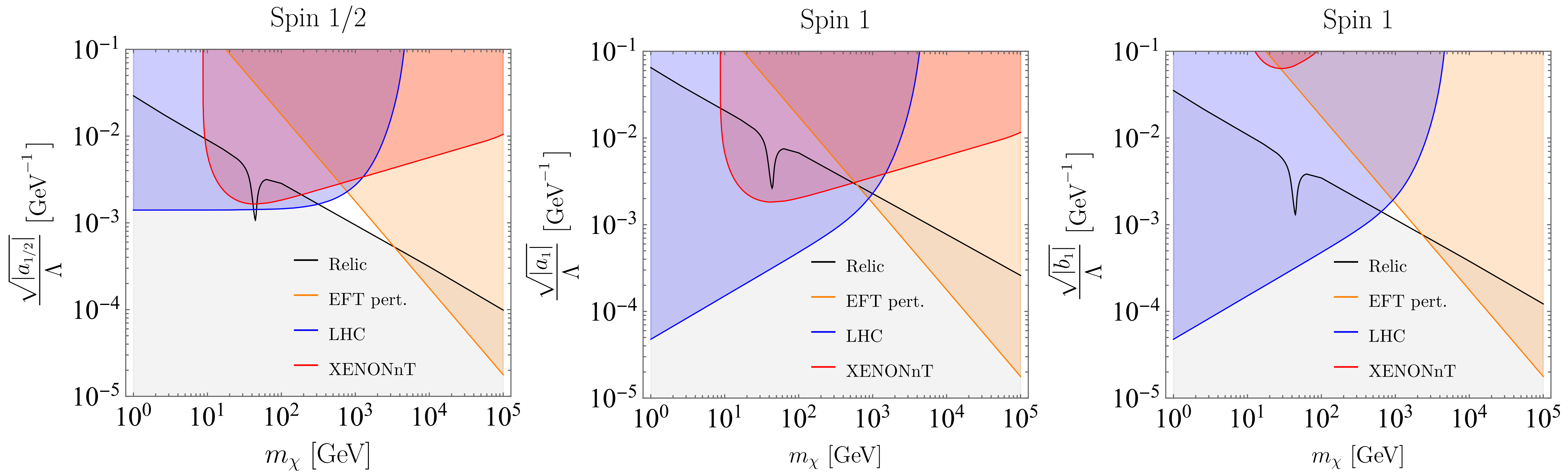
[J. Hisano, A. Ibarra and R. Nagai, JCAP (2020)]

Combined coupling constraints with the naive EFT perterbativity bound



Naive EFT perterbativity bound

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

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

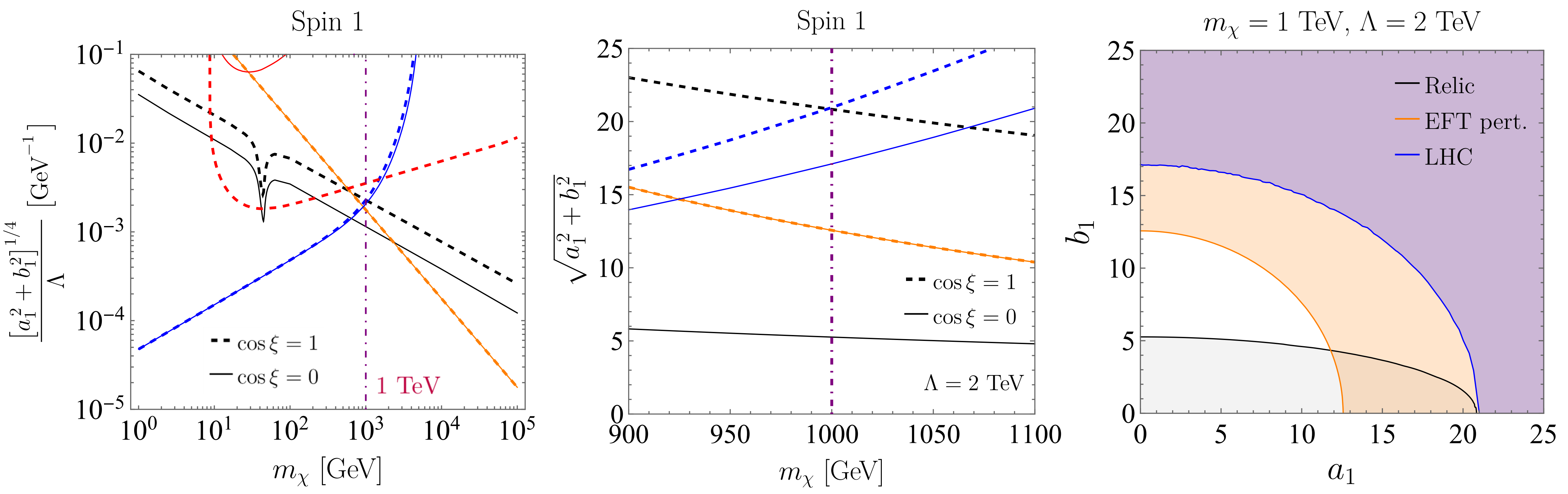
Spin 1/2 $\rightarrow$ Spin 1

✓ Stronger constraints

✓ Completely forbidden coupling combinations

Constraints when both a_1 and b_1 survive?

Combined coupling constraints with the naive EFT perterbativity bound



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

Elliptical behavior of the constraints

Conclusion

1. Introduction to the anapole vertices

2. Coupling constraints imposed by various experiments

   (a) Strong constraints for spin 1

   (b) Completely forbidden coupling region for spin 1

3. Identification of the spin of anapole DM in lepton colliders and of the hypercharge anapole interaction type

4. Tendency of constraint plots for the hypercharge anapole DM of any spin

5. UV scenarios of the hypercharge anapole DM

   (a) Spin 1/2 : Bino, $\cdots$

   (b) Spin 1 : KK excitation of SM particles, $\cdots$

   (c) Spin 3/2 : Gravitino,$\cdots$