Higher-spin particles in physics and in cosmology

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arXiv:2010.02224
arXiv:2102.13652
arXiv:2104.03231
arXiv:2106.09031

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Outline

- Motivations for higher-spin particles
- Effective field theory of any-spin DM
- Freeze-out, freeze-in, direct and indirect detection, collider constraints
- Collider phenomenology and hadronic physics
- Conclusions

Powerful theorems constrain particle spin

- Fundamental massless interacting particles must have s $\leqslant$ 2
  - One, universally coupled graviton
  - Analogous theorems for SUSY
- Particles with s=0, ½, 1, 2 exist. Is s=3/2 the DM?
- The higher spin the more constraints on physical particles
  - For example, in UV-complete theories fundamental s=1 particles must be gauge bosons
- The theorems can be avoided for massive particles, DM can have any spin

Why higher-spin particles?

- There is no accepted theoretical guidance for NP any more.
- Higher-spin hadronic resonances must be described. No consistent theory there!
- Theories of gravity involve higher-spin particles
- Recent string theory papers claim that towers of higher-spin resonances must exist to make string theory contain higher spin.
- Super-heavy DM could be higher-spin, mass> H, 2010.15125

Problems with higher-spin particles: example 1 - gravitino

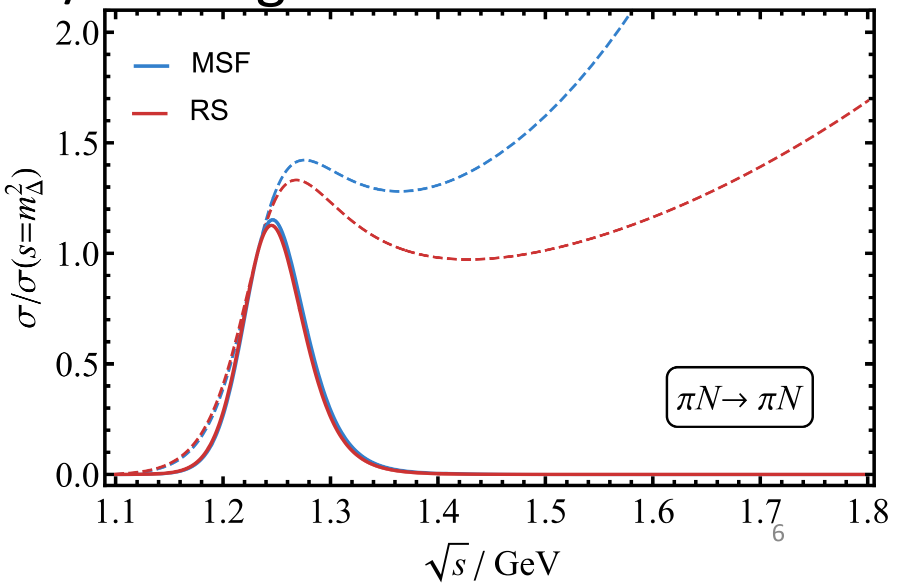
- Rarita-Schwinger (RS) proposed in 1941 a first-order derivative theory for generic spin-3/2 fermion
- The RS field is in Lorentz rep (1,1/2) and contains spin-3/2 field plus unphysical spin-1/2 field (vector-spinor)
- Free RS theory is consistent, interacting theories are in general inconsistent as the unphysical spin-1/2 background causes causality and unitarity violation
- There is only one known way to make RS theory consistent – SUSY – and the spin-3/2 field must be identified with the gravitino

Problems with higher-spin particles: example 2 – hadronic resonances

- The first QCD resonance – the *Δ*-resonance – has spin-3/2

- It is most commonly described by the RS field with ad hoc modified couplings to prevent the unphysical spin-1/2 background to interact

- Our EFT is intrinsically consistent describing a generic massive higher-spin hadronic resonance [2106.09031] [hep-ph]



Weinberg's idea

- Describe massive higher-spin particles with the Lorentz representation

$$(j,0) \oplus (0,j) , \qquad \text{where } j = \text{any spin}$$

- Can describe both Dirac and Majorana particle, contains 2j+1 d.o.f.
- Only physical higher-spin d.o.f. exist, no problems with unphysical d.o.f.
- Examples:
  - The Higgs boson: (0,0)
  - Left- and right-handed electrons: $(1/2,0) \oplus (0,1/2)$
  - Gauge bosons: (1/2,1/2)
  - Gravitino: (1,1/2)
  - Graviton: $(1,1) \oplus (0,0)$

Weinberg's idea – free theory

- Start from the eq. of motion instead of the Lagrangian

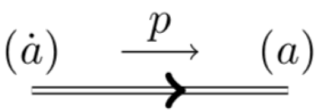
$$\Delta_\psi \equiv 1 + j$$

$$(\Box + m^2)\psi_{(a)} = 0$$

$$\psi_{(a)}(x) = \int \frac{\mathrm{d}^3 p}{(2\pi)^3(2E_{\mathbf{p}})} \sum_\sigma \Big[a_{p\sigma}\, u_{(a)}(p,\sigma) e^{ipx} + a^*_{p\sigma}\, v_{(a)}(p,\sigma) e^{-ipx} \Big]$$

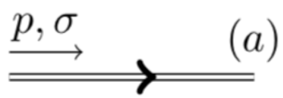
$$\partial^{(\dot a)(a)}\psi_{(a)} = m^{2j}\psi^{\dagger\,(\dot a)}$$

- The propagator has one pole – no ghosts



$$= \frac{ip_{(a)(\dot a)}/m^{2j}}{p^2 - m^2},$$

$$=$$



$$= u_{(a)}(p,\sigma),$$

Weinberg's idea – effective interaction H

- The price to pay – there is no Lagrangian description
- The interactions can be added using effective operators

arXiv:2010.02224

$$\mathcal{H}_{\rm portal} = -\lambda\, \psi^{(a)} \psi_{(a)} \left(|\phi|^2 - v_h^2/2\right) + {\rm h.c.}, \qquad 4 + 2\bar{j}.$$

- We have constructed an EFT for generic, massive any spin particle, we can write down Feynman rules for its interaction and do perturbation theory

- The EFT works below the cut-off scale Λ as any other EFT in particle physics

arXiv:2102.13652
arXiv:2106.09031

Multi-spinor formalism (MSF)

- The Weinberg's proposal has NOT been used for pheno calculations
  - EFT-s have not been that popular
  - SUSY has been popular and the gravitino is a RS field
  - The Weinberg's formalism becomes increasingly complicated for high spin
- Using the MSF the theory becomes simple and usable **arXiv:2010.02224**
- The formalism is common in SUSY using two-spinors l=(1/2,0) and r=(0,1/2). A multi-spinor can be constructed out of those

$$t^{a_1 \ldots a_k \, \dot{a}_1 \ldots \dot{a}_l}_{b_1 \ldots b_k \, \dot{b}_m \ldots \dot{b}_n} \qquad p_{a\dot{a}} = \sigma^{\mu}_{a\dot{a}} p_\mu, \quad \partial_{a\dot{a}} = \sigma^{\mu}_{a\dot{a}} \partial_\mu \qquad \sigma^{\mu}_{a\dot{a}} = (1, \sigma^i)$$

$$\psi_{a_1 \ldots a_{2l} \, \dot{a}_1 \ldots \dot{a}_{2r}}$$

The SM and RS fields can all be expressed using the MSF

Any spin DM

The EFT for DM of any spin

- Assume real (Majorana) rep. (j,0) where j = any spin
- The Higgs portal with complex coupling (parity-even $c_{2\vartheta}$ =+1, -odd $c_{2\vartheta}$ =-1)

$$\mathcal{H}_{\rm portal} = -\lambda\, \psi^{(a)}\psi_{(a)} \left(|\phi|^2 - v_h^2/2\right) + \text{h.c.}, \quad c_{2\theta} \equiv \text{Re}\left[\lambda^2\right]/|\lambda|^2$$

- The possible linear operators

$$\mathcal{H}_{\rm linear} = \frac{1}{\Lambda_{\rm lin}^{\Delta_{\rm SM}+j-3}} \psi \mathcal{O}_{\rm SM} \qquad \Delta_{\rm SM} \geq \begin{cases} 2j & \text{for bosons,} \\ 2j + 3/2 & \text{for fermions} \end{cases}$$

Collider pheno arXiv:2102.13652

- Accidental Z_2 symmetry for j>5/2 (fermions) and j>3 (bosons)

DM abundance from freeze-out

$$\frac{\mathrm{d}Y}{\mathrm{d}x} = -\frac{\langle\sigma v_{\rm rel}\rangle\, s}{xH}\left(Y^2 - Y_{\rm eq}^2\right), \qquad \langle\sigma v_{\rm rel}\rangle = \frac{(2j+1)^2 T}{32\pi^4 n_{\rm eq}^2}\int_{4m^2}^{\infty} \mathrm{d}s\, \sigma(s)\,(s-4m^2)\sqrt{s}\, K_1\left(\frac{\sqrt{s}}{T}\right)$$

$$\Omega h^2 = \frac{8.7\times 10^{-11}}{\mathrm{GeV}^2}\left(\int_{x_f}^{\infty} \mathrm{d}x \langle\sigma v_{\rm rel}\rangle \frac{g_{*s}(T)}{x^2}\right)^{-1}$$

$$\sigma_{\psi\psi\to hh} v_{\rm rel} \sim \frac{|\lambda|^2}{8\pi(2j+1)m^2} \times \left[1 + (-1)^{2j} c_{2\theta} + \frac{2}{3} j(j+1) v_{\rm rel}^2\right], \quad (1$$

$$\sigma_{\psi\psi\to \bar{f}f} v_{\rm rel} \sim \frac{|\lambda|^2 m_f^2}{8\pi(2j+1)m^4} \times \left[1 + (-1)^{2j} c_{2\theta} + \frac{2}{3} j(j+1) v_{\rm rel}^2\right], \quad (1$$

There is a dependence on the spin and on $c_{2\vartheta}$

DM direct and indirect detection

- Direct detection cross section

$$\mathcal{L}_{hN} = \frac{f_N m_N}{v}\overline{N}Nh, \qquad \sigma_N = \frac{2m_N^2\mu_N^2 f_N^2|\lambda|^2}{\pi m_h^4 m^2}\left[1 + c_{2\theta} + \frac{4}{3}j(j+1)\frac{\mu_N^2 v_{\rm rel}^2}{m^2}\right]$$

- Depends most crucially on the value of $c_{2\vartheta}$ – p-wave survives

- Indirect detection: we use constraints on DM DM → bb, WW channels
- The constraints arise from bounds from spheroidal dwarfs

Collider constraints

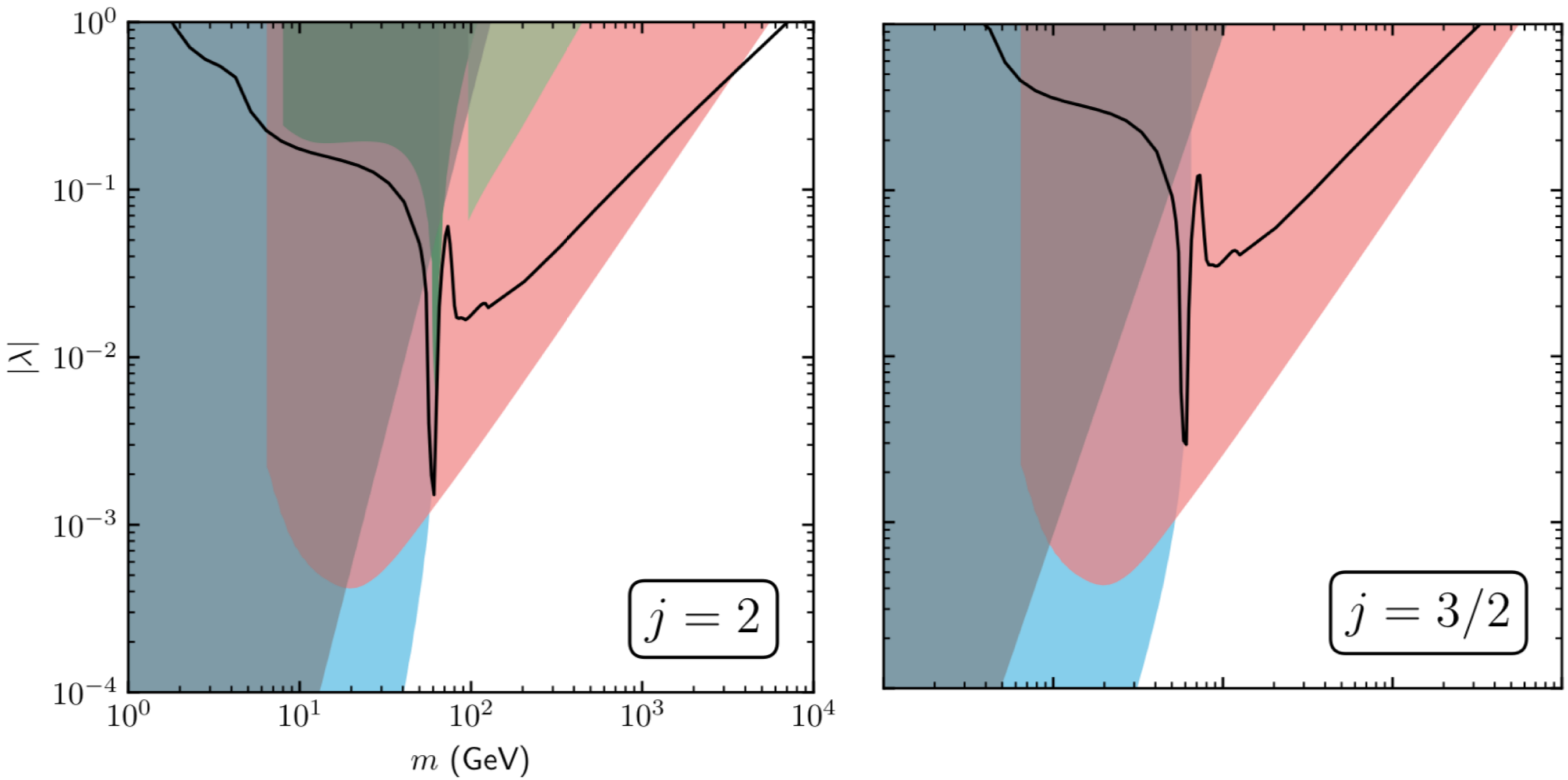
- Direct collider constraints appear from
  - The Higgs invisible BR, h→invisible
  - Non-observation of the missing energy pp → jet + missing energy

$$\mathrm{BR}(h\to\psi\psi)=\frac{\Gamma(h\to\psi\psi)}{\Gamma_h+\Gamma(h\to\psi\psi)},$$

$$\begin{aligned}\Gamma_{h\to\psi\psi}=&\frac{|\lambda|^2 v_h^2 m^2}{2^{2j+3}\pi m_h^3}\\&\times\left[\left(\frac{m_h^2}{m^2}-2+\frac{m_h^2}{m^2}\sqrt{1-\frac{4m^2}{m_h^2}}\right)^{2j+1}\right.\\&\left.-\left(\frac{m_h^2}{m^2}-2-\frac{m_h^2}{m^2}\sqrt{1-\frac{4m^2}{m_h^2}}\right)^{2j+1}\right]\\&+\frac{|\lambda|^2 v_h^2}{4\pi m_h}\sqrt{1-\frac{4m^2}{m_h^2}}(2j+1)(-1)^{2j}c_{2\theta},\end{aligned}$$

The Higgs invisible decay constraints are the most important ones

Freeze-out results, parity-even coupling $c_{2\vartheta}$=1



DM abundance from freeze-in

- The DM abundance is always smaller than the eq. density

$$\frac{\mathrm{d}Y}{\mathrm{d}x} \simeq \frac{\langle \sigma v_{\rm rel}\rangle\, s}{xH} Y_{\rm eq}^2$$

$$\sigma_{\psi\psi\to\bar{f}f} \sim \frac{|\lambda|^2 m_f^2 (1+\delta_{j0})}{(2j+1)^2 \pi m^{4j}} s^{2j-2}$$

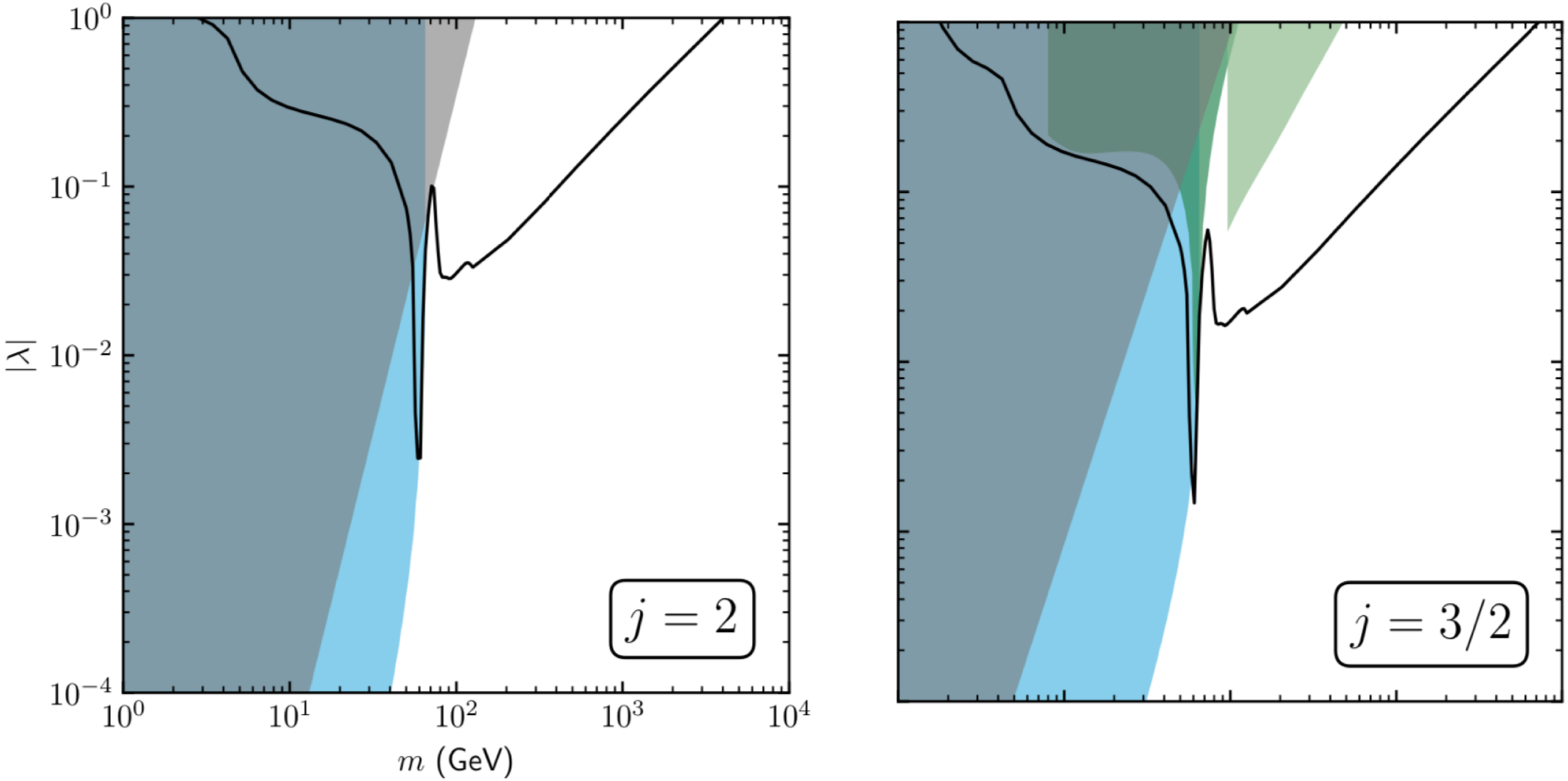
UV-freeze-in

$$\Omega h^2 = 3.4\times 10^{25}\, c_j^2 (2j+1)^2 \int_{T_{\rm min}}^{T_{\rm RH}} \frac{\mathrm{d}T\, m\langle\sigma v_{\rm rel}\rangle}{\sqrt{g_*} g_{*s}}$$

$$|\lambda| \simeq 7\times 10^{-12} \frac{1}{\sqrt{A_j}} \left(\frac{m}{T_{\rm RH}}\right)^{2j-1/2}$$

- The coupling must be so small that no constraints arise, as usual

Freeze-out results, parity-odd coupling $c_{2\vartheta}$=-1



Collider physics

The SM singlet massive spin-3/2 particles

- D=7 operators

$$
\begin{aligned}
-\mathcal{H}_{\text{linear}} = \frac{1}{\Lambda^3}\psi^{abc}_{3/2}\Big[\; & c_q\epsilon^{IJK}u^*_{Ia}d^*_{Jb}d^*_{Kc} + c_l(l^T_a\epsilon l_b)e^*_c + c_{lq}(q^T_{Ia}\epsilon l_b)d^{*I}_c \\
& + c_B\tilde{\phi}^\dagger\sigma^{\mu\nu}_{ab}B_{\mu\nu}l_c + c_W\tilde{\phi}^\dagger\sigma^{\mu\nu}_{ab}\sigma_i W^i_{\mu\nu}l_c + c_\phi\sigma^{\mu\nu}_{ab}(D_\mu\tilde{\phi})^\dagger D_\nu l_c\;\Big] \\
& + \text{h.c.}.
\end{aligned}
$$

- Majorana field, no B or L quantum numbers can be assigned
- L and B creating/violating processes exist

- We classify the interactions accordingly

Decay modes

- 3-body $$\psi_{3/2} \to udd \ , \ \bar{u}\bar{d}\bar{d},$$ $$\psi_{3/2} \to e^+e^-\nu_e \ , \ e^+e^-\bar{\nu}_e, d\bar{d}\nu_e \ , \ d\bar{d}\bar{\nu}_e \ , \ u\bar{d}e^- \ , \ \bar{u}de^+.$$

$$\Gamma(\psi_{3/2} \to f_1 f_2 f_3) = \frac{\kappa_{f_1 f_2 f_3}}{7680\pi^3} \frac{m_{3/2}^7}{\Lambda^6} \ ,$$

- 2-body $$\psi_{3/2} \to W^+e^- \ , \ W^-e^+ \ , \ Z\nu_e \, , \ Z\bar{\nu}_e \, , \ \gamma\nu_e \, , \ \gamma\bar{\nu}_e \, , \ H\nu_e \, , \ H\bar{\nu}_e, .$$

$$\Gamma(\psi_{3/2} \to \gamma\nu_e) = \frac{c_\gamma^2 v^2}{192\pi\Lambda^6} m_{3/2}^5,$$

Branchings

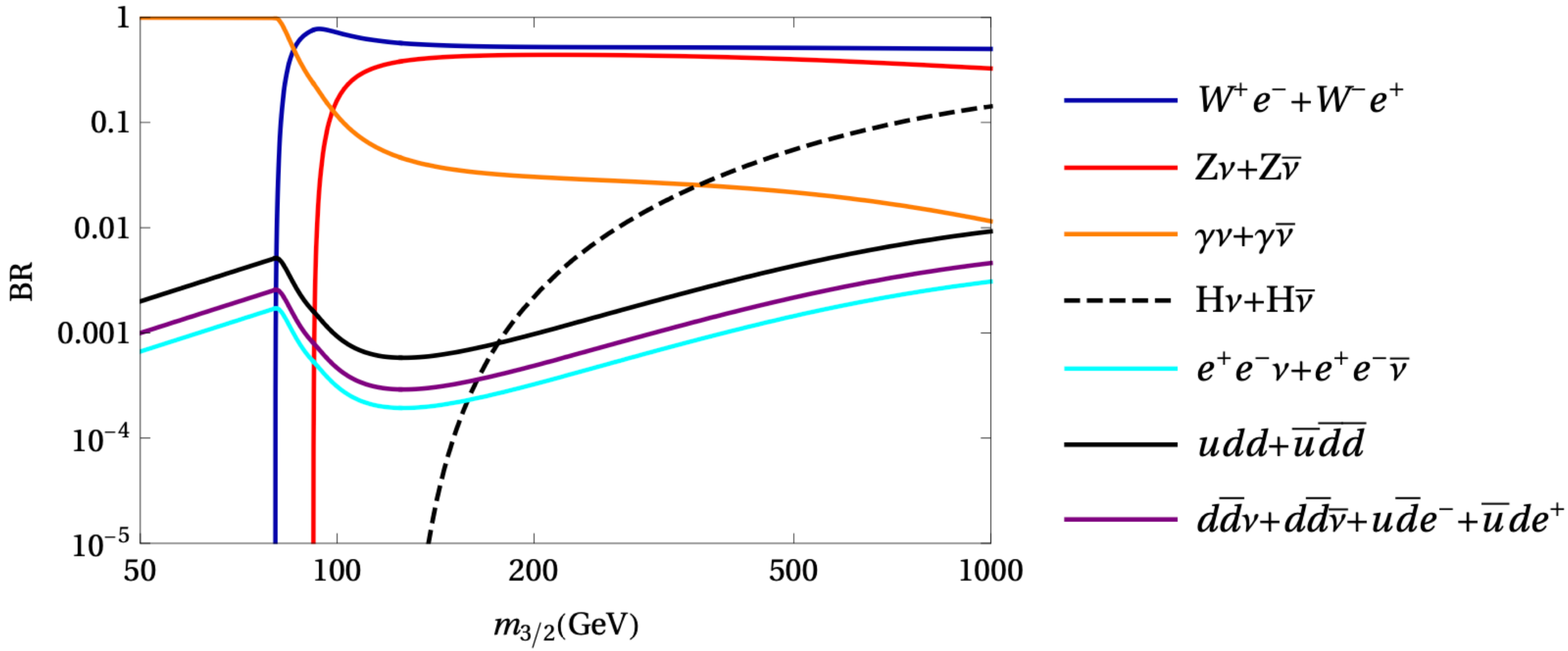


Figure 1. The decay branching ratios of the $\psi_{3/2}$ states into the various final states as functions of $m_{3/2}$ for $\Lambda = 1$ TeV and $c_q = c_l = c_{lq} = c_B = c_W = c_\phi = 1$.

Signatures at hadron colliders

- B=1 $u_R d_R \to \psi_{3/2}\bar{d}_R\,, \quad \bar{u}_R\bar{d}_R \to \psi_{3/2}d_R\,, \quad d_R d_R \to \psi_{3/2}\bar{u}_R\,, \quad \bar{d}_R\bar{d}_R \to \psi_{3/2}u_R\,.$

$$qq \to \psi_{3/2}q \to 4q \quad \Rightarrow \quad pp \to 4j\,.$$

Resembles R-parity violating SUSY

- L=1 $d_L\bar{d}_R \to \psi_{3/2}\bar{\nu}_L\,, \quad \bar{d}_L d_R \to \psi_{3/2}\nu_L\,, \quad u_L\bar{d}_R \to \psi_{3/2}e_L^+\,, \quad \bar{u}_L d_R \to \psi_{3/2}e_L^-\,.$

$$\begin{matrix} qq \to \psi_{3/2}\bar{\nu} \to ee\nu\bar{\nu}\,,\ qq\nu\bar{\nu}\,,\ qqe\nu \\ qq \to \psi_{3/2}e \to eee\nu\,,\ qqe\nu\,,\ qqee \end{matrix} \quad \Rightarrow \quad pp \to eeE_{\mathrm{T}}^{\mathrm{mis}}, eeeE_{\mathrm{T}}^{\mathrm{mis}}, qqE_{\mathrm{T}}^{\mathrm{mis}}, qqeE_{\mathrm{T}}^{\mathrm{mis}}, qqee\,,$$

Resembles SUSY signatures

Massive spin-2 particle at colliders

- Interactions

$$-\mathcal{H}_{\text{linear}} = \frac{1}{\Lambda^3}\psi_2^{abcd}\Big[c_B\sigma_{ab}^{\mu\nu}\sigma_{cd}^{\rho\lambda}B_{\mu\nu}B_{\rho\lambda} + c_W\sigma_{ab}^{\mu\nu}\sigma_{cd}^{\rho\lambda}W_{i\mu\nu}W^i_{\rho\lambda} + c_G\sigma_{ab}^{\mu\nu}\sigma_{cd}^{\rho\lambda}G_{A\mu\nu}G^A_{\rho\lambda}\Big] + \text{h.c.}, \tag{3.1}$$

- Decays and production $\psi_2 \to \gamma\gamma,\ ZZ,\ Z\gamma,\ WW,\ gg.$

$$\hat{\sigma}(gg \to \psi_2) = \frac{16\pi c_G^2}{3}\frac{m_2^8}{\hat{s}^{3/2}\,\Lambda^6}\delta(\sqrt{\hat{s}} - m_2).$$

Unlike the graviton, spin-2 couples only to gauge bosons

Delta-resonance

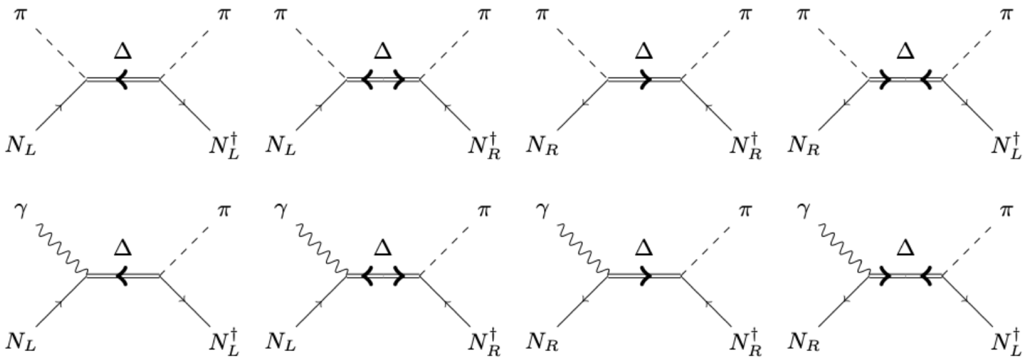
A model of Delta-resonance

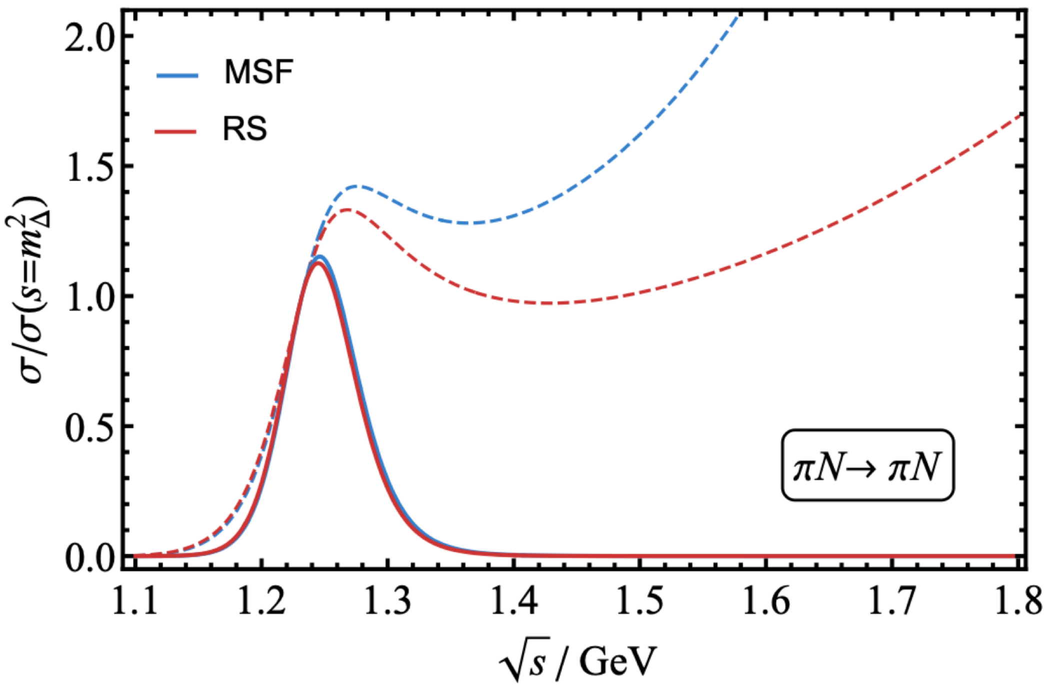
- EFT for hadrons

Field	Lorentz irrep	Isospin	Hypercharge	Dimension
π	$(0,0)$	1	0	1
N_L	$(1/2,0)$	$1/2$	$1/2$	$3/2$
N_R	$(0,1/2)$	$1/2$	$1/2$	$3/2$
Δ_L	$(3/2,0)$	$3/2$	$1/2$	$5/2$
Δ_R	$(0,3/2)$	$3/2$	$1/2$	$5/2$
F_L	$(1,0)$	0	0	2
F_R	$(0,1)$	0	0	2

$$-\mathcal{H}_{\pi N\Delta} = \frac{c_\pi}{\Lambda^3}\Big[\partial^{a}_{\dot{b}}(N_R)^{\dagger\, a}\partial^{\dot{b}c}\pi_A T_A(\Delta_L)_{abc}$$
$$+\,\partial_{\dot{a}b}(N_L)^{\dagger}_{\dot{b}}\partial^{b}_{\dot{c}}\pi_A T_A(\Delta_R)^{\dot{a}\dot{b}\dot{c}}\Big] + \text{h.c.}\,,$$
$$-\mathcal{H}_{\gamma N\Delta} = \frac{c_\gamma}{\Lambda^2}\Big[F^{ab}(N_L)^{c}T_3(\Delta_L)_{abc}$$
$$+\,F_{\dot{a}\dot{b}}(N_L)_{\dot{c}}T_3(\Delta_L)^{\dot{a}\dot{b}\dot{c}}\Big] + \text{h.c.}\,.$$

Our theory vs RS





The interactions are in principle distinguishable

Conclusions

- We have written down and worked out physically consistent EFT for a generic, massive any-spin particle
- This employs Weinberg's (j,0) reps and multi-spinor formalism
- Physically consistent calculations of DM, collider phenomenology and hadronic resonances becomes possible
- The higher-spin particles behave as generic WIMPs, the suppression of direct detection bounds for parity-odd couplings is general, collider phenomenology resembles the one of SUSY and extra dim.