Higher spin particles: dark matter and high energy colliders

Niko Koivunen

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Representations

- Particles are in irreducible representations of Poincare group, defined by mass and spin.
- Lorentz group has two subgroups: $SU(2)_L$ and $SU(2)_R$.
- Ambiguity when assigning particle into irreducible representation of Lorentz group: "two spins", left- and right-handed: (j_L, j_R)

Spin	Rep	DOF	Example	Rep	DOF
0	$(0,0)$	1	KG	$(0,0)$	1
$\frac{1}{2}$	$(\frac{1}{2},0)$	2	ψ_L	$(\frac{1}{2},0)$	2
1	$(\frac{1}{2},\frac{1}{2})$	4	gauge	$(1,0)$	3
$\frac{3}{2}$	$(\frac{1}{2},1)$	8	SUSY	$(\frac{3}{2},0)$	4
2	$(1,1)$	16	gravity	$(2,0)$	5
$j>2$	?	?	?	$(j,0)$	$2j+1$

$(j, 0) \oplus (0, j)$

- Originally Weinberg used $(j, 0) \oplus (0, j)$ to describe any spin (1964)[1]
- The representation $(j, 0) \oplus (0, j)$ has the correct number of degrees of freedom for massive fields
- This allows to avoid the usual problems of higher-spin fields (non-physical degrees of freedom tend to reappear as ghost in interacting theories)
- Practically useful reformulation of Weinberg's original was presented in *Criado, Koivunen, Raidal, Veermäe*, arXiv:2010.02224 [hep-ph] (PRD)

[1] Weinberg, Phys. Rev. **133**, B1318 (1964)

Multispinor formalism $(j,0) \oplus (0,j)$

- Use fully symmetric "multispinor", $\psi_{a_1 \ldots a_{2j}} = \psi_{(a)}$, to represent spin-j field (j = any spin!):

$$\psi_{(a)}(x) = \int \frac{d^3 p}{(2\pi^3)(2E_p)} \sum_\sigma \left[\hat{a}_\sigma(p) u_{(a)}(p,\sigma) e^{ipx} + \hat{a}^\dagger_\sigma(p) v_{(a)}(p,\sigma) e^{-ipx} \right]$$

- Satisfies equations of motion (order-2j in derivatives(!)):

$$i\partial^{(\dot{a})(a)} \psi_{(a)} = m^{2j} \psi^{\dagger(\dot{a})} \quad \text{and} \quad (\Box + m^2)\psi_{(a)} = 0$$

- Propagator (only single pole!):

$$S(p) = i \frac{p_{(a)(\dot{a})}}{p^2 - m^2}$$

- Mass dimension of $\psi_{(a)}$ is $j+1 \Rightarrow$ EFT

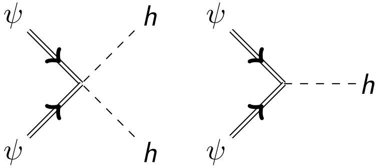
No problems

- Correct number of degrees of freedom (the higher derivatives in equations of motion are not a problem)
- The propagator is well defined (no additional poles, no ghosts!)
- Simple to use: multispinor: $S(p) = i\frac{p_{(a)(\dot{a})}}{p^2-m^2}$
  Weinberg:
  $S(p)^{(2)} = -i\frac{(-p^2)^2-2p^2(\vec{p}\cdot\vec{J})(\vec{p}\cdot\vec{J}-p^0)+\frac{2}{3}(\vec{p}\cdot\vec{J})\left[(\vec{p}\cdot\vec{J})^2-|\vec{p}|^2\right]\left[\vec{p}\cdot\vec{J}-2p^0\right]}{p^2-m^2}$
- The multispinor framework is effective field theory that allows fully consistent computations bellow the cut-off scale Λ (just like in any EFT)
- This formulation is the first practical and consistent framework that allows the study of higher spin particles!

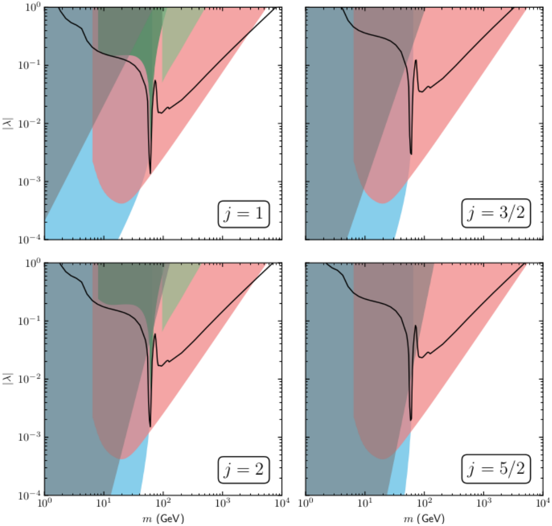
Feynman rules

- The free theory is well behaving
- One can add interactions at will. Interaction do not cause trouble, as only physical DOFs are present from the start
- Simplest interaction to study: Higgs portal:

$$\mathcal{L} = \frac{\lambda}{\Lambda^{2j}} (H^\dagger H) \psi^{(a)} \psi_{(a)} + h.c.$$



Any spin dark matter



Phenomenology

The any spin framework has been used in phenomenological studies of:

- Dark matter: arXiv:2010.02224 [hep-ph] (PRD)
- Collider phenomenology arXiv:2102.13652 [hep-ph] (JHEP)
- $(g-2)_\mu$: arXiv:2104.03231 [hep-ph]
- Δ-resonance: arXiv:2106.09031 [hep-ph]

Possibilities:

- Baryogenesis, leptogenesis
- Preheating, reheating
- More collider phenomenology

Summary

- This is the first practical and consistet framework that allows for study of higher spin particles!
- *Criado, Koivunen, Raidal, Veermäe*, arXiv:2010.02224 [hep-ph] (PRD),
  Criado, Djouadi, Koivunen, Raidal, Veermäe, arXiv:2102.13652 [hep-ph] (JHEP),
  Criado, Djouadi, Koivunen, Müürsepp, Raidal, Veermäe, arXiv:2104.03231 [hep-ph]
  Criado, Djouadi, Koivunen, Müürsepp, Raidal, Veermäe, arXiv:2106.09031 [hep-ph]