

Title: Theory and Phenomenology of Continuous Spin Particles

Speakers:

Series: Particle Physics

Date: October 07, 2022 - 1:00 PM

URL: <https://pirsa.org/22090084>

Abstract: Massless particles are always assumed to have Lorentz invariant helicity. However, the generic massless particles allowed by Lorentz invariance and quantum mechanics are "continuous spin particles," whose infinitely many discrete helicity states mix under little group transformations by an amount determined by the spin scale. Previous work at the Perimeter Institute has shown that CSPs have well-behaved soft emission amplitudes, are described by a simple free field theory, and reduce to the photon or graviton at momenta above the spin scale. In this talk, I will show how to couple CSP fields to classical particles. When treating on-shell CSP emission and absorption, the resulting dynamics are causal and readily calculable. Remarkably, they are also unique, depending on only the spin scale. This opens the door to precision experiments which probe the spin scale of the photon and graviton.

Zoom Link: <https://pitp.zoom.us/j/94728811371?pwd=Y3RoRnJuUzNzT0FmRVFiazI5czc5Zz09>

Theory and Phenomenology of Continuous Spin Particles

Kevin Zhou



Perimeter Institute Seminar — October 7, 2022

arXiv:2210.xxxxx

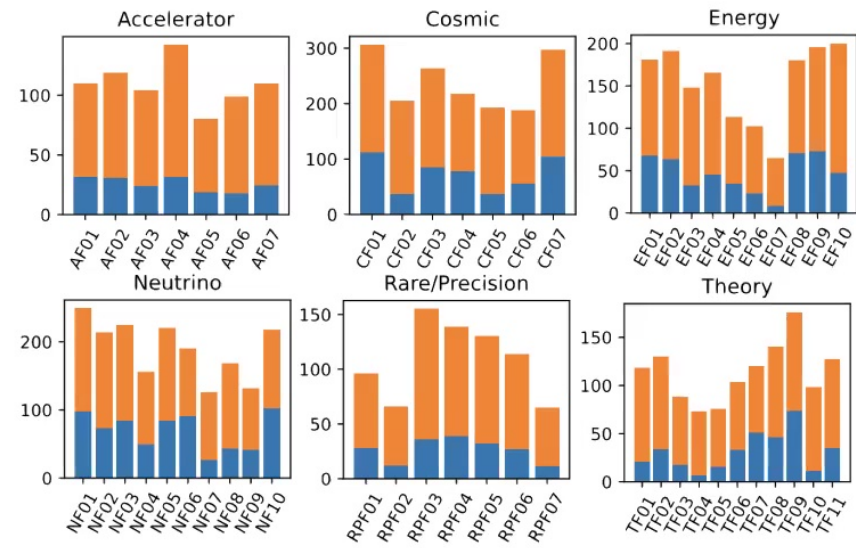
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Particle Physics Then and Now

Testing the Standard Model Electroweak QCD etc.
Beyond the Standard Model Technicolor Supersymmetry Grand Unification etc.
Limits of Accelerator Technology and Novel Accelerator Ideas
Novel Detector Ideas

Snowmass 1982 Summary



Snowmass 2021 Interest Survey (2203.07328)

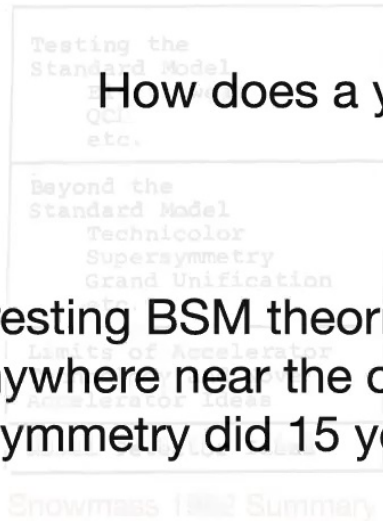
DISCOVERY	COMMENTS	ODDS*
Standard Model Higgs	As good as discovered, some say	2-1
Big surprises	Expect the unexpected	2-1
Supersymmetry	Too beautiful to be wrong?	5-1

2007 Fermilab survey

Particle Physics Then and Now

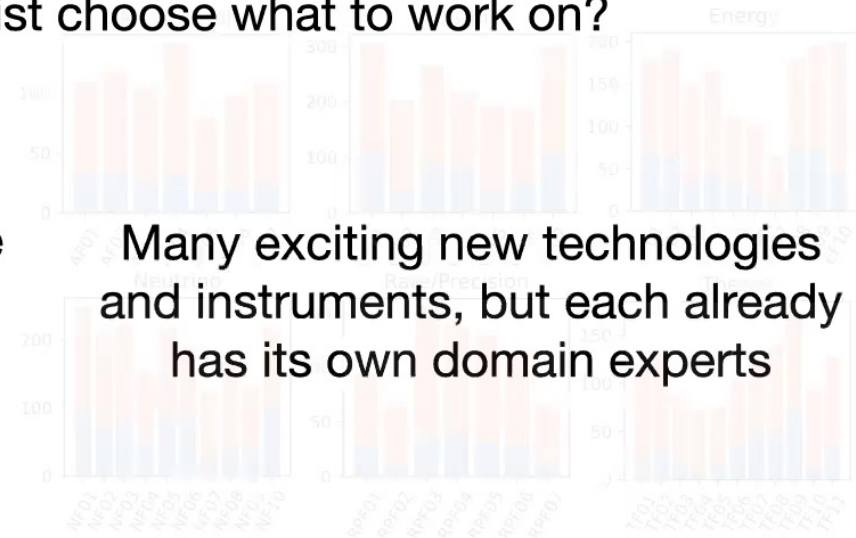
How does a young scientist choose what to work on?

Many interesting BSM theories, but none has anywhere near the odds that supersymmetry did 15 years ago!



Category	Sub-category	Percentage
Standard Model	QCD	~45%
	etc.	~5%
Beyond the Standard Model	Technicolor	~15%
	Supersymmetry	~15%
	Grand Unification	~15%
Limit of Accelerator		~10%
Accelerator		~10%

2007 Fermilab survey



Many exciting new technologies and instruments, but each already has its own domain experts

Snowmass 2011 Survey

Particle Physics Then and Now

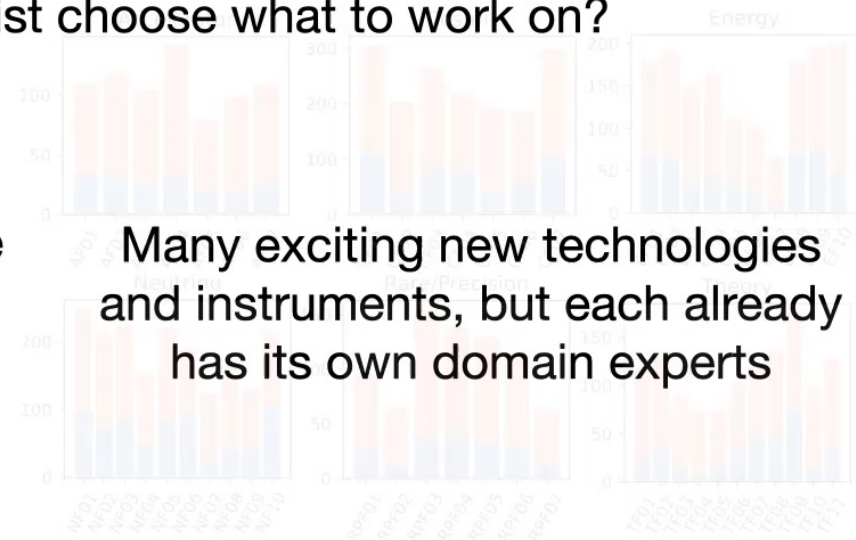
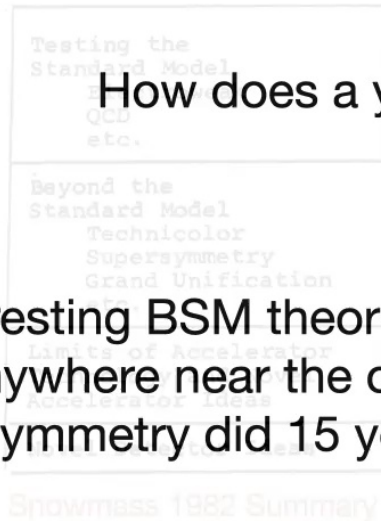
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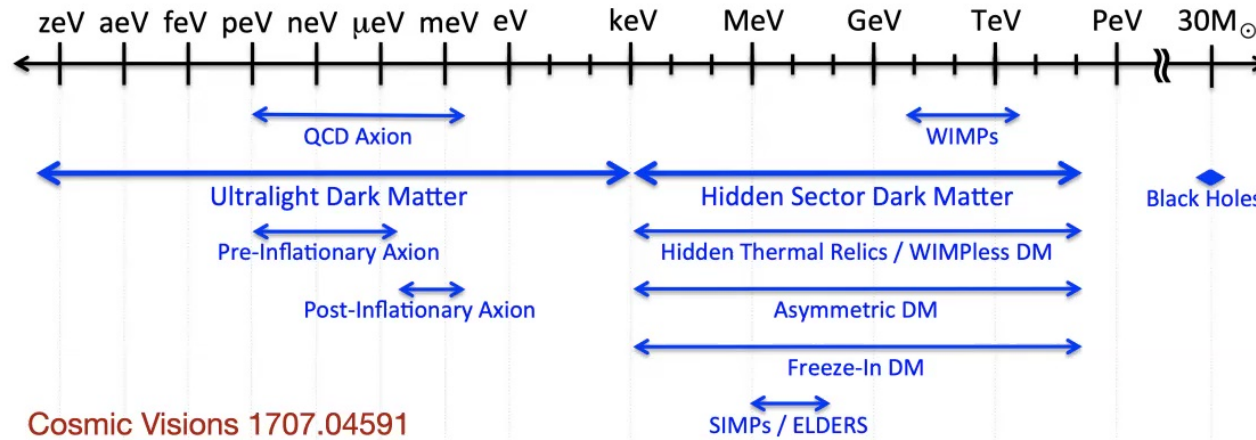
Many exciting new technologies and instruments, but each already has its own domain experts

Another path: linking theories and the technologies that can test them, across fields

Physics is a big place — many exciting connections have not been made!



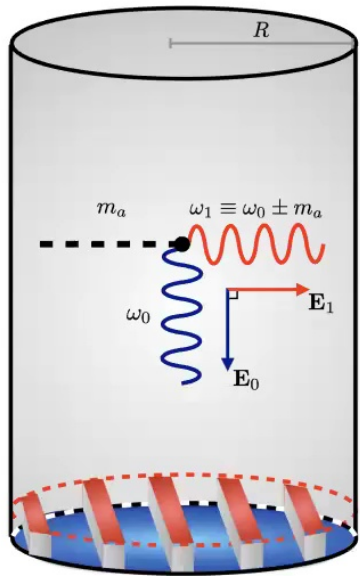
Case Study: Dark Matter



In current situation, we would like to both decisively test canonical models, and probe broadly into underexplored classes of models

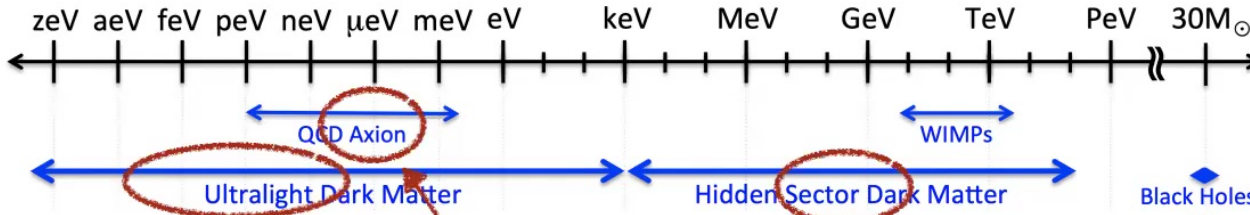
New experimental programs can help do both!

Case Study: Dark Matter

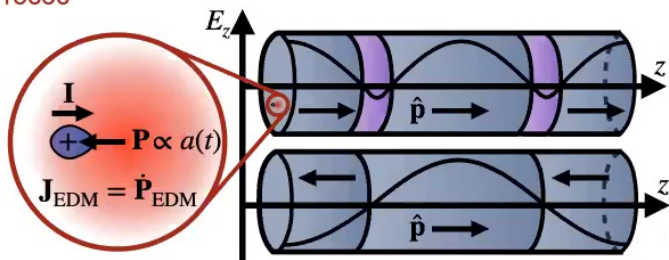


axion

upconversion
1912.11048, 2007.15656

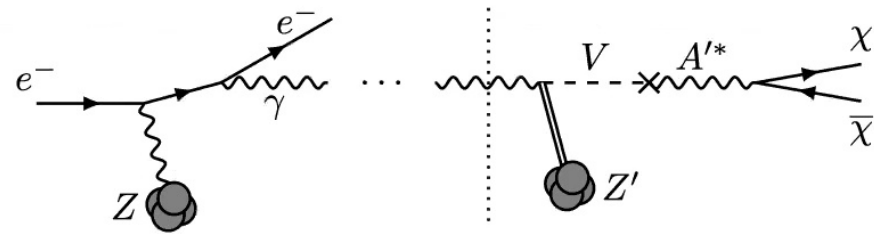


polarization haloscopes

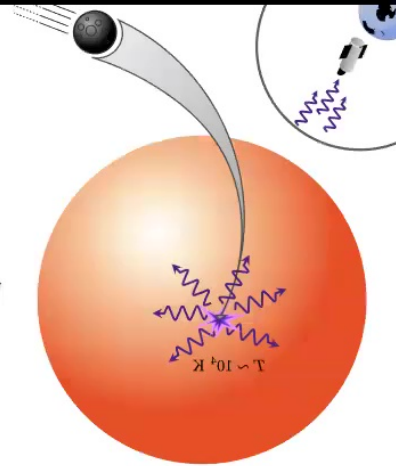


2209.12901

invisible meson decays




2112.02104




stellar shock
transients

2106.09033



Today's talk is **not** about dark matter.
It's about how to experimentally resolve a foundational
open question in relativistic quantum field theory.



Same spirit of making new links between theory and
experiment, but here the challenge was developing
the formalism far enough to make predictions

Massless Particles

Quantum mechanics and special relativity strongly restrict the types of particles which can exist in our world

Wigner's classification (1939)

$p^\mu = 0$ vacuum expectation value

$p^2 < 0$ tachyon (instability)

$p^2 = 0$ massless particle

$p^2 > 0$ massive particle (m, J)

Massless Particles

Massless bosons mediate long-range forces, but are highly constrained

Weinberg's soft theorems (1965)

$p^2 = 0$ massless particle

$h = 0$ fine-tuned (not seen)

$|h| = 1$ couples to conserved charge (photon)

$|h| = 2$ couples to stress-energy (graviton)

$|h| > 2$ cannot interact (not seen)

Massless Particles

This is an elegant story: everything allowed by general principles plays a role

However, in the **generic** massless particle representation, historically called a “continuous spin particle” (CSP), helicity states mix under Lorentz transformations

$$\begin{array}{ll} \dots & \dots \\ \text{-----} h = 2 & \text{-----} h = 3/2 \\ \text{-----} h = 1 & \text{-----} h = 1/2 \\ \text{-----} h = 0 & \text{-----} h = -1/2 \\ \text{-----} h = -1 & \text{-----} h = -3/2 \\ \text{-----} h = -2 & \dots \\ \dots & \end{array}$$

bosonic CSP fermionic CSP
(not covered here)

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----- $h = 2$	----- $h = 3/2$
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----- $h = -1$	----- $h = -3/2$
----- $h = -2$...
...	

bosonic CSP fermionic CSP
(not covered here)

Why doesn't the CSP appear in textbooks?

History, technical difficulty

Why doesn't the CSP appear in nature?

We **don't know** if it does!

Continuous Spin Particles

Previous work at Perimeter has shown CSP physics is potentially well-defined:

Weinberg soft theorems?

assume Lorentz invariant \hbar

generalizes to well-behaved CSP soft factors

Schuster and Toro, JHEP (2013) 104

Incompatible with field theory?

Simple free field action found

Schuster and Toro, PRD (2015)

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Ruled out by thermodynamics?

No, for small enough ρ

(in prep)

Experimentally irrelevant?

Only three classes of CSP interactions, like scalars/gauge bosons/gravitons as $\rho \rightarrow 0$

Suggests known massless particles could be CSPs!

Schuster and Toro, JHEP (2013) 105

Continuous Spin Particles

Previous work at Perimeter has shown CSP physics is potentially well-defined:

Weinberg soft theorems?
assume Lorentz invariant \hbar

Incompatible with field theory?
Simple free field action found

generalizes to well-behaved CSPs of arbitrary spin
Schuster and Toro, PRD (2015)

Strange and unfamiliar?

Absolutely!

Ruled out by thermodynamics?
No, for small enough ρ
(in prep)

Experimentally irrelevant?

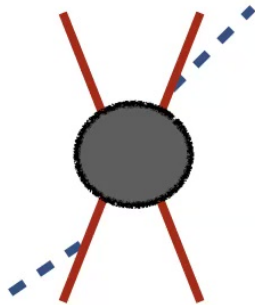
Only three classes of CSP interactions, like
scalars/gauge bosons/gravitons as $\rho \rightarrow 0$

But CSPs are a theoretically motivated **infrared** deformation of familiar gauge theories, which may play a role in the resolution of long-standing puzzles

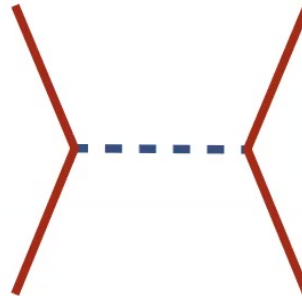
Subcase: known massless particles
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Continuous Spin Particles

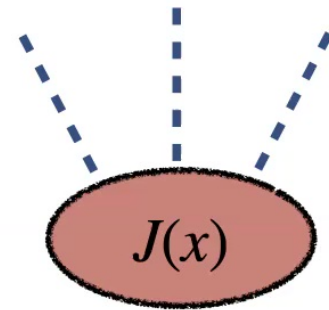
Until now, it has been unclear how to test if photons or gravitons are CSPs



Unique amplitudes for soft emission and absorption, but limited applicability



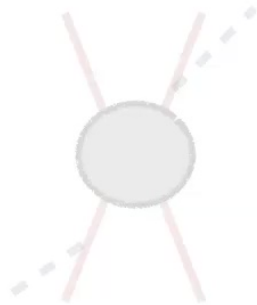
Consistent ansatzes for CSP exchange amplitudes, but not unique



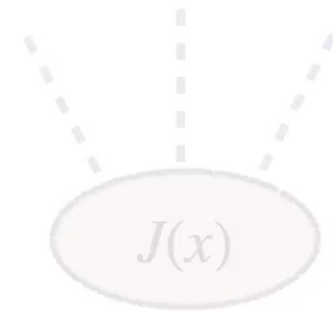
Field theory can couple to current, but no dynamic sources of current known

Continuous Spin Particles

Until now, it has been unclear how to test if photons or gravitons are CSPs



We now know how to couple
matter particles to CSP fields!



Results for radiation emission or absorption are **unique**,
leading to sharp predictions and specific tests

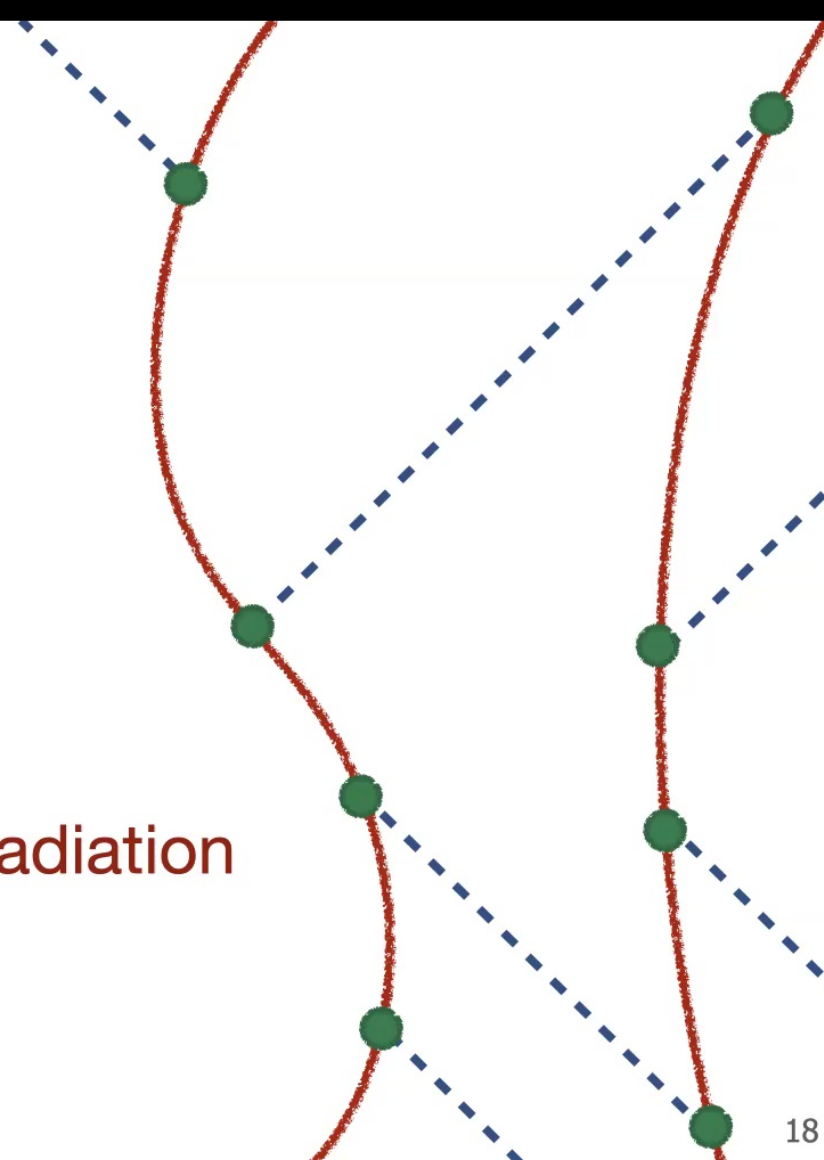
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absorption and
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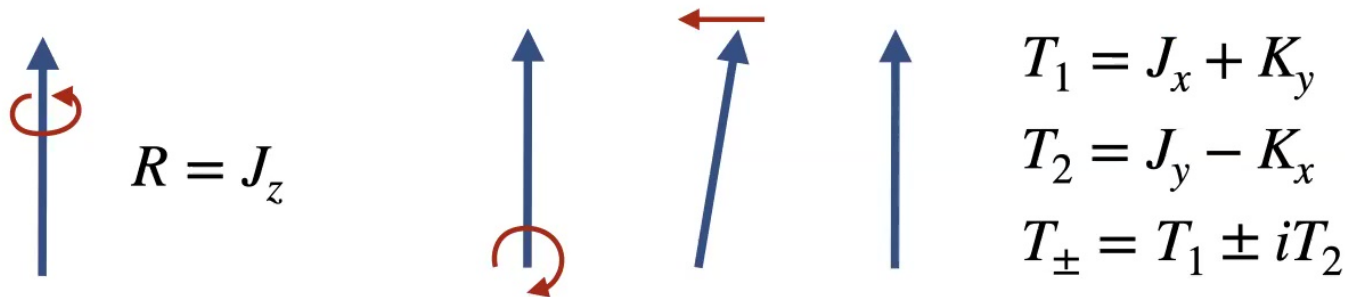
Outline

- The free CSP field
- Coupling matter particles to fields
- Emission and absorption of CSP radiation



Massless Particles

- Particles retain their identity when translated, boosted, or rotated (i.e. their state space is a representation of the Poincare group)
- A particle's internal degrees of freedom determined by action of Lorentz transformations that keep the particle momentum fixed (little group elements)
- For a massless particle, $k^\mu = (\omega, 0, 0, \omega)$, these are:



Massless Particles

- The eigenvalue of R is helicity, $R|h\rangle = h|h\rangle$, **always** integer or half-integer
- The T_{\pm} operators must raise and lower helicity, $T_{\pm}|h\rangle = \rho|h \pm 1\rangle$

Massless Particles

- The eigenvalue of R is helicity, $R|h\rangle = h|h\rangle$, **always** integer or half-integer
- The T_{\pm} operators must raise and lower helicity, $T_{\pm}|h\rangle = \rho|h \pm 1\rangle$
 - Usual treatment assumes degenerate limit $\rho = 0$, only one helicity state
 - General case is CSP with spin scale ρ , all integer or half-integer helicities (focus on the integer case)

Actions for All Helicities

- Warm up: write a field that creates particles of any integer helicity, at $\rho = 0$
- For helicity h particles, simplest possible field is a rank h symmetric tensor
- Convenient way to package all h simultaneously uses auxiliary four-vector η^μ

$$\Psi(\eta, x) \sim \phi(x) + \eta^\mu A_\mu(x) + \eta^\mu \eta^\nu h_{\mu\nu}(x) + \dots$$

(with trace subtractions, normalizations)

- For $|h| \geq 1$, gauge symmetry required to get correct degrees of freedom

Actions for All Helicities

- The desired action turns out to be

$$S[\Psi] = \frac{1}{2} \int d^4x [d^4\eta] \left(\delta'(\eta^2 + 1) (\partial_x \Psi)^2 + \frac{1}{2} \delta(\eta^2 + 1) (\partial_x \cdot \partial_\eta \Psi)^2 \right)$$

- Integration over hyperboloid has geometric meaning, needs regularization:

$$\int [d^4\eta] \delta(\eta^2 + 1) = \int [d^4\eta] \delta'(\eta^2 + 1) \equiv 1$$

- Integrals of η -space functions just produce tensor contractions, e.g.

$$\int [d^4\eta] \delta(\eta^2 + 1) \eta^\mu \eta^\nu = -\frac{1}{4} g^{\mu\nu} \quad \int [d^4\eta] \delta'(\eta^2 + 1) \eta^\mu \eta^\nu = -\frac{1}{2} g^{\mu\nu}$$

Actions for All Helicities

- To see how this works, consider the scalar component $\Psi(\eta, x) = \phi(x)$

$$S[\Psi] = \frac{1}{2} \int d^4x [d^4\eta] \left(\delta'(\eta^2 + 1) (\partial_x \Psi)^2 + \frac{1}{2} \delta(\eta^2 + 1) (\partial_x \cdot \partial_\eta \Psi)^2 \right)$$

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$$= \frac{1}{2} \int d^4x (\partial_x \phi)^2$$

- Trivially recovers massless scalar field action

Actions for All Helicities

- As another example, consider the vector component $\Psi(\eta, x) = \sqrt{2} \eta^\mu A_\mu(x)$

$$S[\Psi] = \frac{1}{2} \int d^4x [d^4\eta] \left(\delta'(\eta^2 + 1) (\partial_x \Psi)^2 + \frac{1}{2} \delta(\eta^2 + 1) (\partial_x \cdot \partial_\eta \Psi)^2 \right)$$

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Actions for All Helicities

- As another example, consider the vector component $\Psi(\eta, x) = \sqrt{2} \eta^\mu A_\mu(x)$

$$\begin{aligned}
 S[\Psi] &= \frac{1}{2} \int d^4x [d^4\eta] \left(\underbrace{\delta'(\eta^2 + 1)(\partial_x \Psi)^2}_{(\sqrt{2} \eta_\mu \partial_x A^\mu)^2} + \frac{1}{2} \delta(\eta^2 + 1) \underbrace{(\partial_x \cdot \partial_\eta \Psi)^2}_{(\sqrt{2} \partial_\mu A^\mu)^2} \right) \\
 &= \int d^4x \left(-\frac{1}{2} (\partial_\mu A_\nu)^2 + \frac{1}{2} (\partial_\mu A^\mu)^2 \right) = -\frac{1}{4} \int d^4x F_{\mu\nu} F^{\mu\nu}
 \end{aligned}$$

- Recovers massless vector field action; more generally, recovers linearized gravity at rank 2, and known Fronsdal action at general h , with appropriate gauge symmetries

Actions for All Helicities

- Dynamical content: plane wave radiation described by

$$\Psi_{\pm h, k} = e^{-ik \cdot x} (\eta \cdot \epsilon_{\pm})^h$$

and annihilated by T_{\pm} as expected

- Accounting for gauge redundancy, this is a complete basis for solutions
- Rank in η corresponds to helicity $|h|$, so one can easily go back to conventional tensor notation

The CSP Action

- The free CSP action is very similar:

$$S[\Psi] = \frac{1}{2} \int d^4x [d^4\eta] \left(\delta'(\eta^2 + 1)(\partial_x \Psi)^2 + \frac{1}{2} \delta(\eta^2 + 1)((\partial_x \cdot \partial_\eta + \rho) \Psi)^2 \right)$$

Contains all helicities, has required gauge symmetries and right limit as $\rho \rightarrow 0$

↗

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$$S[\Psi] = \frac{1}{2} \int d^4x [d^4\eta] \left(\delta'(\eta^2 + 1)(\partial_x \Psi)^2 + \frac{1}{2} \delta(\eta^2 + 1)((\partial_x \cdot \partial_\eta + \rho) \Psi)^2 \right)$$

Contains all helicities, has required gauge symmetries and right limit as $\rho \rightarrow 0$

- Harmonic gauge plane wave solutions indeed related by T_\pm , and take the form

$$\Psi_{\pm h, k} = e^{-ik \cdot x} e^{-i\rho \eta \cdot q} (\eta \cdot \epsilon_\pm)^h \quad q \cdot k = 1$$

- No longer definite order in η ! Tensor expansion not useful, η -space essential.

Outline

- The free CSP field
- **Coupling matter particles to fields**
- Emission and absorption of CSP radiation

Coupling Currents to Fields

- Scalar fields: $S_{\text{int}} = \int d^4x \phi(x) J(x)$ $\partial_x^2 \phi(x) = J(x)$

- Vector fields: $S_{\text{int}} = \int d^4x A_\mu(x) J^\mu(x)$ $\partial_x^2 A^\mu(x) = J^\mu(x)$

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- CSP fields: $S_{\text{int}} = \int d^4x [d^4\eta] \delta'(\eta^2 + 1) J(\eta, x) \Psi(\eta, x)$ $\partial_x^2 \Psi(\eta, x) = J(\eta, x)$
(includes scalar, vector, tensor, ...)

Coupling Currents to Fields

- Scalar fields: $S_{\text{int}} = \int d^4x \phi(x) J(x)$ $\partial_x^2 \phi(x) = J(x)$
- Vector fields: $S_{\text{int}} = \int d^4x A_\mu(x) J^\mu(x)$ $\partial_x^2 A^\mu(x) = J^\mu(x)$
 $\partial_\mu J^\mu = 0$
- CSP fields: $S_{\text{int}} = \int d^4x [d^4\eta] \delta'(\eta^2 + 1) J(\eta, x) \Psi(\eta, x)$ $\partial_x^2 \Psi(\eta, x) = J(\eta, x)$
(includes scalar, vector, tensor, ...)
- Gauge invariance of S_{int} implies continuity condition $(\partial_\eta \cdot \partial_x + \rho) J(\eta, x) = 0$
on $\eta^2 + 1 = 0$

Currents From Particles

- For low-energy precision experiments, consider classical particle matter
- Current of particle must obey Poincare invariance and continuity condition
- Assuming leading currents are local to worldline and depend only on $z^\mu(\tau)$ and $\dot{z}^\mu(\tau)$ yields unique currents for scalars and vectors

$$J(x) = g \int d\tau \delta^4(x - z(\tau)) \quad J^\mu(x) = e \int d\tau \frac{dz^\mu}{d\tau} \delta^4(x - z(\tau))$$

- Determines both how particles source field, and how they're acted on by field

$$\frac{dp^\mu}{d\tau} = g \partial^\mu \phi(z(\tau)) \quad m \frac{d\dot{z}^\mu}{d\tau} = e \dot{z}_\nu F^{\mu\nu}(z(\tau))$$

Building CSP Currents

- The CSP current and (strong) continuity condition in Fourier space are

$$\tilde{J}(\eta, k) = \int d\tau e^{ik \cdot z(\tau)} f(\dot{z}, k, \eta) \quad (-ik \cdot \partial_\eta + \rho)f = 0$$

- Implies f depends on k , so current not perfectly localized to worldline

Building CSP Currents

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- Implies f depends on k , so current not perfectly localized to worldline
- Apparently many possibilities for f , such as

$$f = e^{-i\rho\eta \cdot V/k \cdot V} \quad V = \begin{cases} \dot{z} & \text{temporal} \\ k - \dot{z}(\dot{z} \cdot k) & \text{spatial} \end{cases}$$

- Essential singularities at $k \cdot V = 0$ make evaluation in space tricky

Static Fields

- Computing static field requires regulating essential singularities at $\omega = 0$ (temporal current) or $|\vec{k}| = 0$ (spatial current), but result well-behaved:

$$\psi(\eta, \vec{r}, t) = \frac{1}{r} \times \begin{cases} J_0\left(\sqrt{2\rho\eta^0 t}\right) & \text{temporal current} \\ J_0\left(\sqrt{2\rho(|\vec{\eta}||\vec{r}| - \vec{\eta} \cdot \vec{r})}\right) & \text{spatial current} \end{cases}$$

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- Finding velocity-dependent forces is hard; unclear how general answers are
- Interestingly, currents seem to require substructure on scale $1/\rho$, yet still reduce to familiar localized currents as $\rho \rightarrow 0$

Radiation Fields

- An easier first question: emission and absorption of on-shell radiation ($k^2 = 0$)
- Spatial current simplifies to

$$f = \underbrace{\exp\left(-i\rho \frac{\eta \cdot \dot{z}}{k \cdot \dot{z}}\right)}_{\text{temporal current}} \underbrace{\exp\left(i\rho \frac{\eta \cdot k}{(k \cdot \dot{z})^2}\right)}_{1 + \hat{f}}$$

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- Harmonic gauge condition implies \tilde{f} does not contribute to S_{int} !

Our core technical result: this phenomenon is **completely general!**

Radiation Fields

- For on-shell CSPs, **all** currents are equivalent to

$$f = h(k \cdot \dot{z}) \exp\left(-i\rho \frac{\eta \cdot \dot{z}}{k \cdot \dot{z}}\right)$$

- Correspondence to ordinary massless particles at $\rho = 0$ gives three options

$$h \sim \begin{cases} g & \text{scalar CSP} \\ e k \cdot \dot{z} & \text{vector CSP} \\ m (k \cdot \dot{z})^2 & \text{graviton CSP} \end{cases}$$

- Motivates finding corrections to radiation emission and forces from radiation absorption, for vector CSP photons (focus of this talk) and graviton CSPs

Outline

- The free CSP field
- Coupling matter particles to fields
- **Emission and absorption of CSP radiation**

Emission of Vector CSPs

- Computing the harmonic n , helicity h radiation emitted from a non-relativistic charged particle in periodic motion is a straightforward exercise:

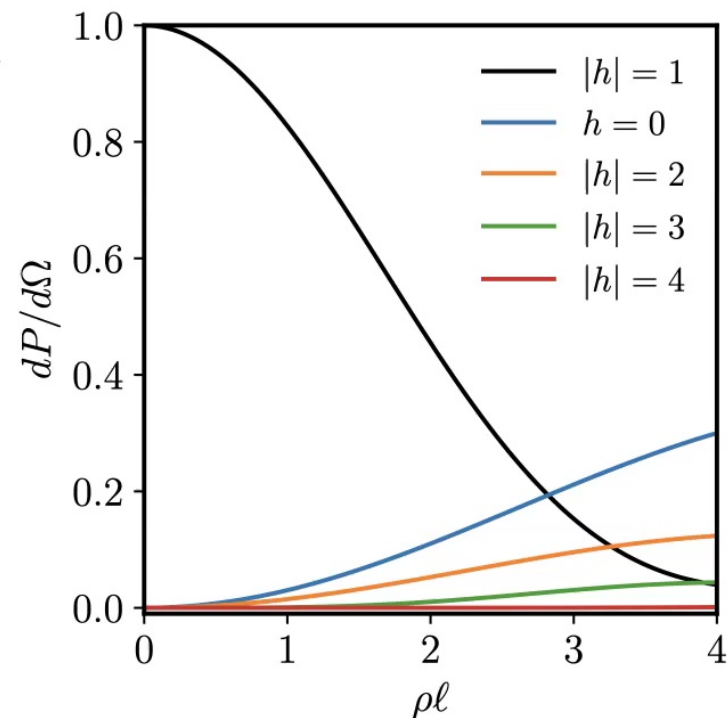
$$\frac{dP_{n,h}}{d\Omega} \propto q^2 \left| \int_0^T \frac{dt}{T} n^2 e^{in\omega_0 t} e^{-ih \arg(\epsilon_+ \cdot v_\perp)} J_h \left(\frac{\rho |v_\perp(t)|}{n\omega_0} \right) \right|^2$$

Emission of Vector CSPs

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- Yields ordinary Larmor formula at $\rho = 0$
- Leading correction is $(\rho v_0/\omega)^2 = (\rho \ell)^2$
suppressed emission of $h = 0, 2$ modes
- Corrections negligible in UV, $\ell \ll 1/\rho$



Forces From Vector CSPs

- Computing the dynamics of a particle in helicity h CSP radiation background is another straightforward exercise:

$$L_{\text{int}}[\mathbf{z}(\tau), \mathbf{v}(\tau)] \propto \underbrace{\psi_{h,k}(\mathbf{z}, \tau)}_{\text{field amplitude}} \underbrace{(1 - \hat{\mathbf{u}} \cdot \mathbf{v}) \tilde{J}_h \left(\frac{\rho}{\omega} \frac{\boldsymbol{\epsilon}_{\pm} \cdot \mathbf{v}}{(1 - \hat{\mathbf{u}} \cdot \mathbf{v})} \right)}_{\text{series in } \rho \mathbf{v}}$$

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- Contains Lorentz force law, with distinctive velocity-dependent corrections:
 - $O(\rho v)$ forces from $h = 0$ (parallel to \mathbf{v}_{\perp}) and $h = 2$ (like grav. wave)
 - $O((\rho v)^2)$ forces from $h = 1$ (parallel to \mathbf{v} , violating Lorentz force law)

Open Questions

Core experimental question: most effective probes of the photon/graviton spin scale ρ

Cosmological and astrophysical
bounds, CSP radiation background

Light shining through wall and
helioscope searches

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Understanding CSP currents off-shell (near field)



Velocity-dependent modifications of force laws

Quantizing CSP-coupled matter



Atomic absorption/emission

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Non-Abelian structure (Yang–Mills, general relativity)? Higgs mechanism?

Deeper understanding of the origin of CSP-coupled currents?

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Much more physics to consider and discover!