Title: Spin and Long-Range Forces: The Unfinished Tale of the Last Massless Particle

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Abstract: The success of gauge theory descriptions of Nature follows simply, in hindsight, from Lorentz symmetry, quantum mechanics, and the existence of interacting massless particles with spin. Yet, remarkably, the most generic type of massless particle spin has never been seriously examined: Wigner's so-called "continuous spin" particles (CSPs), which have a tower of polarization states carrying all integer or half-integer helicities that mix under boosts.   I will explain recent progress in understanding these particles on two fronts: simple scattering amplitudes and a free quantum field theory. The scattering amplitudes give two remarkable insights into CSP physics. First, Lorentz symmetry protects CSP interactions from the dysfunction one might expect in a theory with infinitely many polarization states: divergent cross-sections and problematic thermodynamics. Second, and most intriguingly, CSP interactions approach those of ordinary scalars or helicity-1 or 2 gauge bosons in a high-energy "correspondence" regime. While a full interacting theory of CSPs remains elusive, these results suggest that any such theory would extend Maxwell electrodynamics and/or general relativity in a viable and testable way.

Spin and Long-Range Forces:

The Unfinished Tale of the Last Massless Particle

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based on work with Philip Schuster

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& to appear

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Symmetry and Geometry are Inevitable

consequences of QM + Relativity

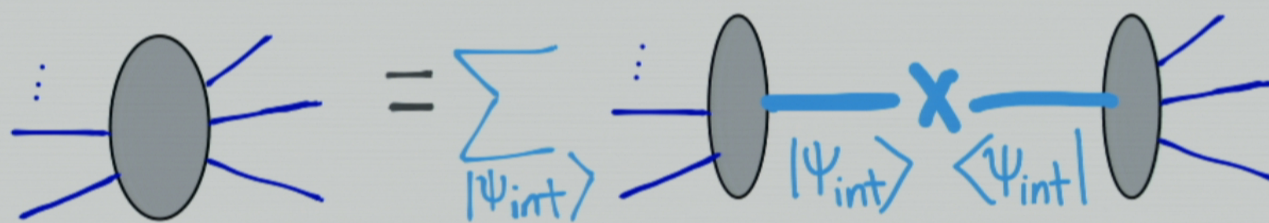
Weinberg 1964, Phys Rev B

Symmetry and Geometry are Inevitable

consequences of QM + Relativity

[Weinberg 1964]

Unitary *transition amplitudes*



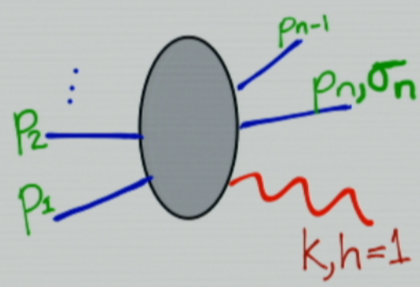
can constrain complex amplitudes by relating them to simpler ones

Symmetry and Geometry are Inevitable

consequences of QM + Relativity

[Weinberg 1964]

external states = particles labelled by momentum, spin



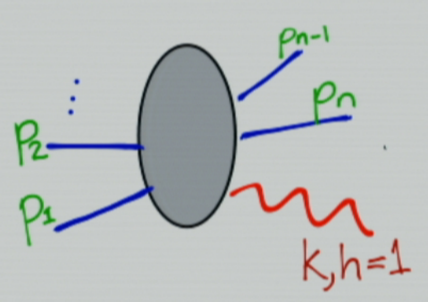
Symmetry and Geometry are Inevitable

consequences of QM + Relativity

[Weinberg 1964]

For massless h=1 particle:

$$\mathcal{A} = \epsilon^{\mu}_{\pm}\mathcal{M}_{\mu}(\dots), \quad k.\mathcal{M} = 0$$



p_{n-1}
p_n
p_2
p_1
k,h=1

Symmetry and Geometry are Inevitable

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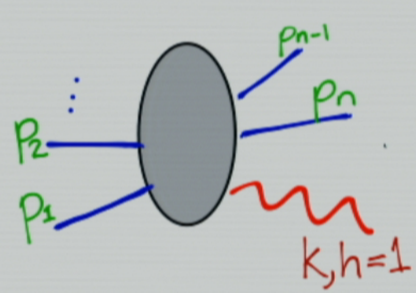

For soft (low-momentum) particle:

unitary ⇒ emission from external legs dominates

Symmetry and Geometry are Inevitable

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[Weinberg 1964]

For massless h=1 particle:

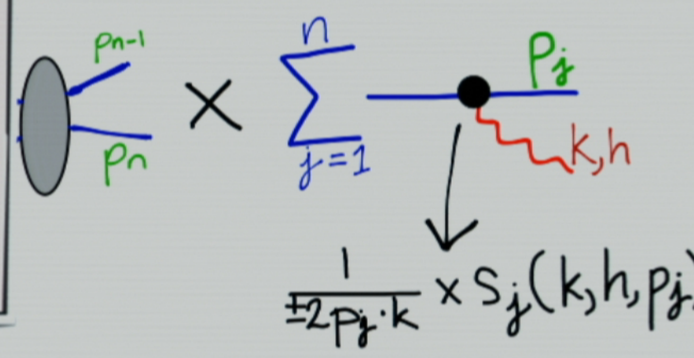
$\epsilon_{\pm}^{\mu}\mathcal{M}_{\mu}(\ldots), \quad k.\mathcal{M} = 0$

Unique solution:

$$s_j = g_j \epsilon_{\pm}.p_j$$

"charge" is conserved

$$\sum g_i^{(IN)} = \sum g_i^{(OUT)}$$



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Symmetry and Geometry are Inevitable
consequences of QM + Relativity
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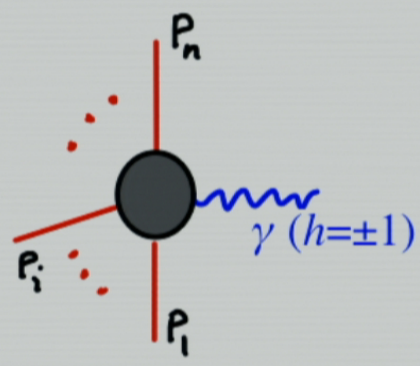
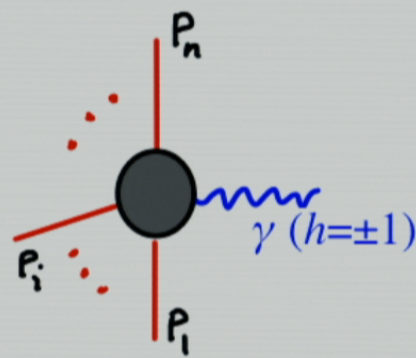
Symmetry and Geometry are Inevitable



QM + Relativity

- $\Rightarrow$ γ couples to conserved charge
- $\Rightarrow$ symmetry (Abelian or non-Abelian
- $\Rightarrow$ like charges repel, $\vec{\mathrm{E}}$ and $\vec{\mathrm{B}}$ forces, …

Symmetry and Geometry are Inevitable



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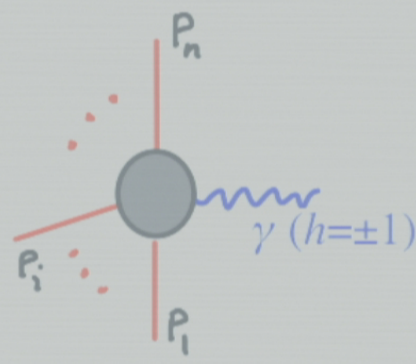

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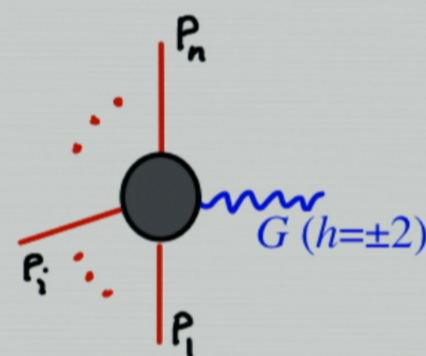
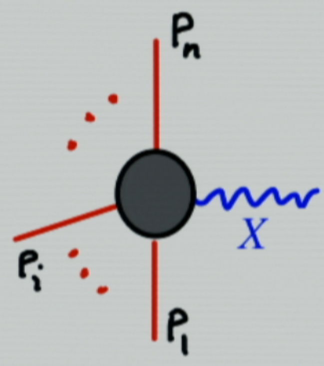


QM + Relativity

- $\Rightarrow$ ***universal*** coupling to momentum; universal attraction
- $\Rightarrow$ self-coupling
- $\Rightarrow$ geometric structure of GR

γ (h=±1)
P_n
P_i
P_1
G (h=±2)

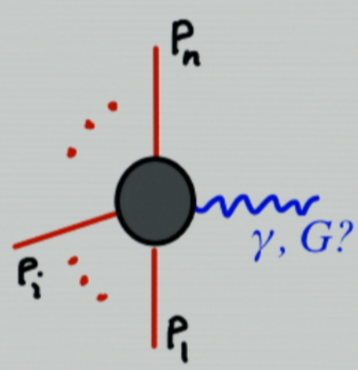
What else could there be?



h=3 or higher

$\Rightarrow$ No Lorentz-invariant interaction strong enough to mediate long-range force

What else could there be?



Another type of massless spin

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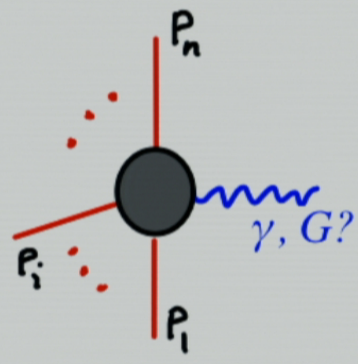


Another type of massless spin

infinite tower of ***integer*** helicity eigenstates that mix under Lorentz

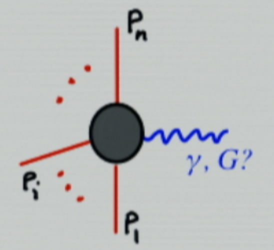
(Wigner's "continuous spin" particles = CSP for short)

Clearly relevant to the question of inevitable gauge +gravity…

Not known if there's a consistent theory...and no good counter-argument.

Fundamental open problem in long-distance physics – and it will have ***testable*** consequences!

Clean Counter-Arguments That Weren't



- Lorentz+QM in Single Soft-emission
  excludes helicity-3 and higher…

  consistent, almost unique CSP-emission amplitudes exist!

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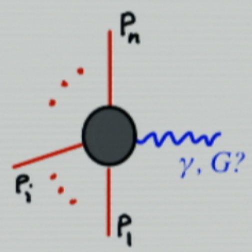

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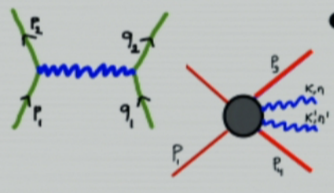
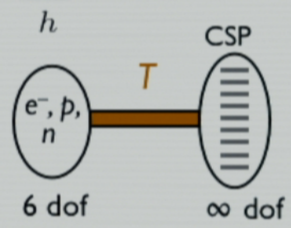


- Lorentz+QM in multi-CSP and exchange amplitudes?
  consistent ansatz for both (maybe not uniquely fixed)

$$\sum_h |\mathcal{A}_h|^2 < \infty$$



- Problems with infinite tower of states?
  e.g. divergent cross-sections, problematic thermodynamics

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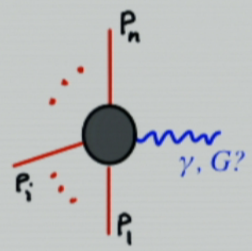

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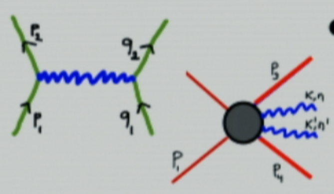

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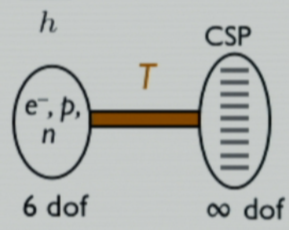


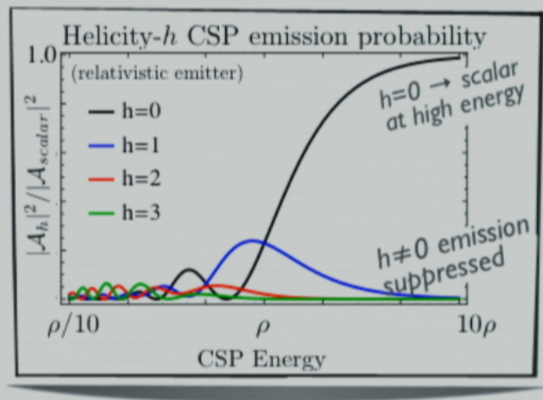
- Problems with infinite tower of states?
  e.g. divergent cross-sections, problematic thermodynamics

  Solved by Lorentz-invariance

- Incompatible with field theory?

$$\mathcal{L}_{\text{free}} \propto (\partial_x \Phi)^2 - \frac{\eta^2}{2}(\Delta\Phi)^2$$

Most intriguing of all…



Although a CSP has an ∞ tower of states, Lorentz-invariant amplitudes do not couple to them equally.

Consistent interaction amplitudes fall into three types. In their high-energy limits, familiar helicity 0, 1, and 2 amplitudes emerge.

Can all long-range phenomena arise from ***one class*** of massless particles?

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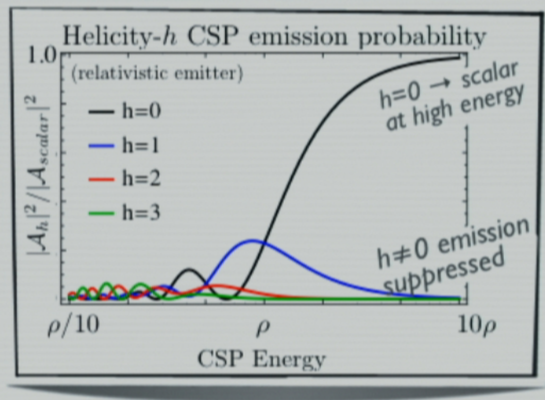

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Can all long-range phenomena arise from ***one class*** of massless particles?


h=2
h=3
h≠0 emission suppressed
ρ/10
ρ
10ρ
CSP Energy
Consistent intera
types. In their hi
0, 1, and 2 amplit
Can all long-rang
class of massless

Outline

1. Long-Range Forces and Inevitable Symmetry

Kinematics

2. The Last Massless Particle

Mathematical Physics

3. Can CSPs interact consistently?
   - soft-emission amplitudes
   - scalar (h=0) correspondence
   - highlights of local gauge theory

Testable Physics

4. Physics of CSP Correspondence
   - gauge and GR correspondence
   - thermodynamics and tests of continuous spin physics

Spin As Usual

Massive

Spin: action of rotations $\vec{\mathbf{J}}$ on state

SO(3)≃SU(2) algebra

Invariant

$$\vec{\mathbf{J}}^2|\psi\rangle_s = s(s+1)|\psi\rangle_s$$

Massless

Helicity = action of momentum-axis rotation, $\vec{\mathbf{J}}.\hat{p}$

SO(2)=U(1) algebra

Invariant eigenvalue

$$\vec{\mathbf{J}}.\hat{p}|h\rangle = h|h\rangle$$

Spin As Usual

Massive

Spin: action of rotations $\vec{\mathbf{J}}$ on state

depends on reference frame

SO(3)≃SU(2) algebra

*discontinuous **number** of generators?*

Invariant

$$\vec{\mathbf{J}}^2|\psi\rangle_s = s(s+1)|\psi\rangle_s$$

Massless

Helicity = action of momentum-axis rotation, $\vec{\mathbf{J}}.\hat{p}$

SO(2)=U(1) algebra

Invariant eigenvalue

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Massive Particle Spin

What's special about rotations?

Rotations $|\sigma, \vec{v}=0\rangle \xrightarrow{R} |\sigma', \vec{v}=0\rangle$

Rotation generators $\vec{\mathbf{J}}$ preserve $\vec{v} = 0$

$\Rightarrow$ action on ***spin only*** forms representation of rotation group

Massive Particle Spin

Rotation generators $\vec{\mathbf{J}}$ preserve rest frame

Obvious relativistic generalization:

Lorentz transf. Λ_{LG} that preserve particle's momentum p^μ: $|\sigma, p^\mu\rangle \xrightarrow{\Lambda_{LG}} |\sigma', p^\mu\rangle$

generators: $\vec{\mathbf{J}} \to W_\mu = \frac{1}{2}\epsilon_{\mu\nu\rho\sigma} J^{\nu\rho} p^\sigma$
orthogonal to p

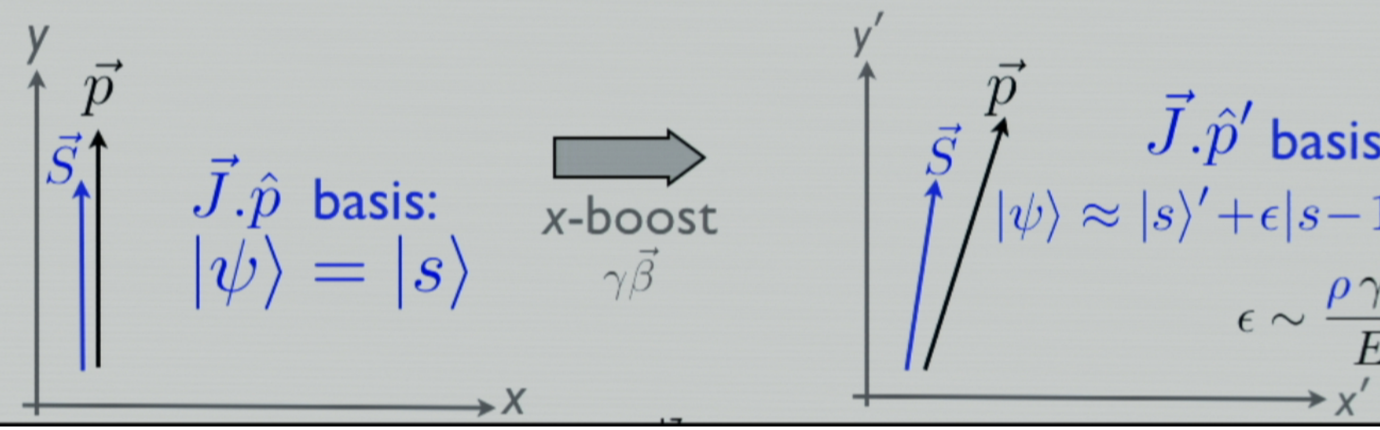
Relativistic Massive Spin

The natural relativistic invariant is **dimensionful**

spin-s: $W^2 \to -\underbrace{m^2 s(s+1)}_{\rho^2}$

consider energetic particle spin-aligned with $\vec{p}$

spin gets mis-aligned by boost

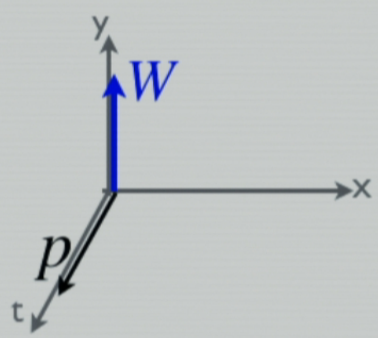


Massless Spin: A Bifurcation

Two ways of solving $p.W = 0$ for massless particles

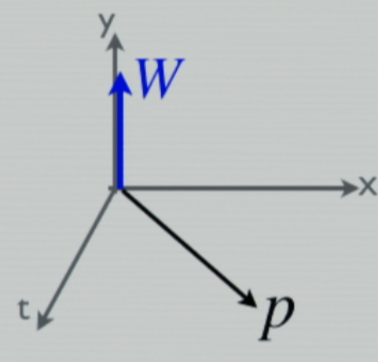
Massive:
p timelike

W spacelike

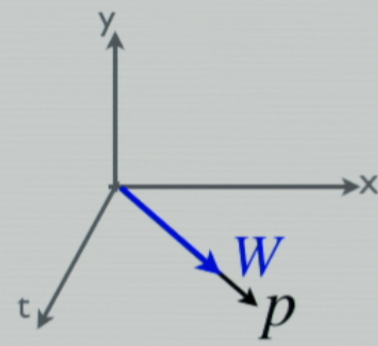


Massless:
p null $\Rightarrow$

W spacelike **or** $W^\mu \propto p^\mu$



→ continuous spin



→ familiar L-I helicity

Momentum-Preserving Lorentz Generators

Generators = 3 components of W^μ
work as in massive case.

– Helicity-rotation $\mathbf{R} = \vec{\mathbf{J}}.\hat{p}$

– 2 x less familiar generators (transverse rot+boost)

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eigenstates $\mathbf{R}|h\rangle = h|h\rangle$ h=(½)-integer

– 2 x less familiar generators (transverse rot+boost)

→ raising/lowering operators (like massive $\mathbf{J}_\mathrm{x} \pm i\mathbf{J}_\mathrm{y}$)

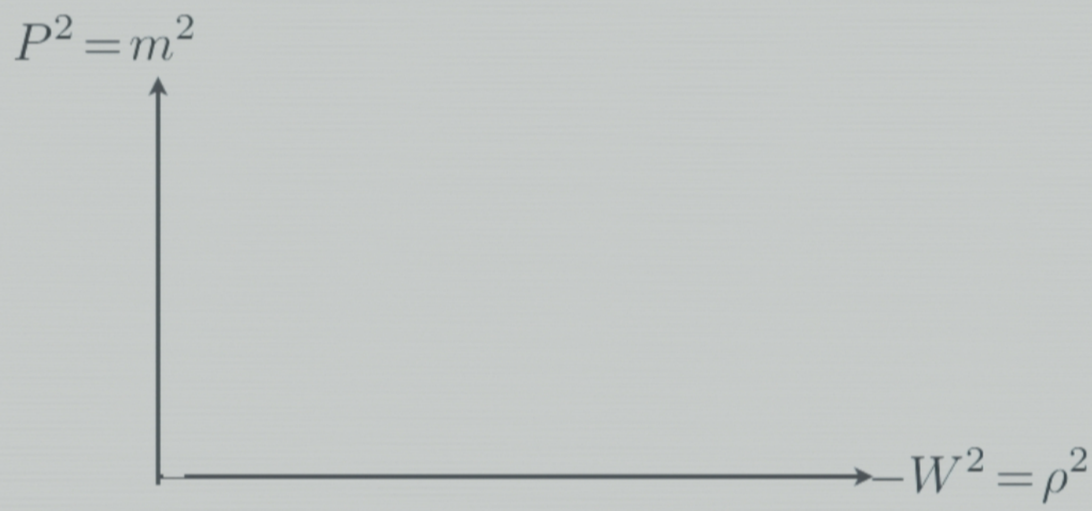
$$\mathbf{W}_\pm|h\rangle = \rho|h \pm 1\rangle$$

coeff. indep of h with
units of ***momentum***

$$\Rightarrow W^2|h\rangle = -\rho^2|h\rangle$$

The Menu of (Integer) Spins in 4D

CSPs generalize
(to bosons and fermion
in ≥3 dimensions



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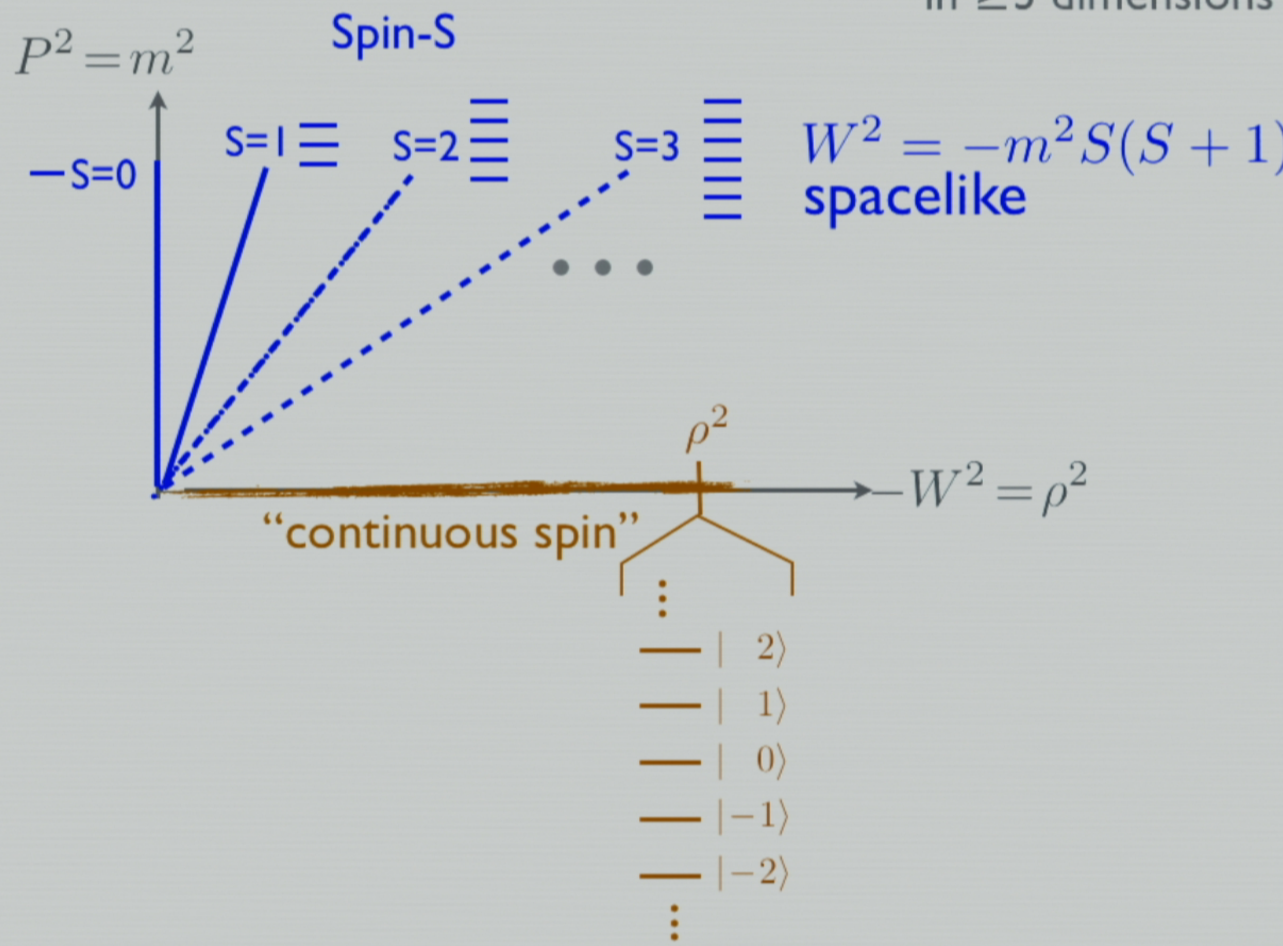
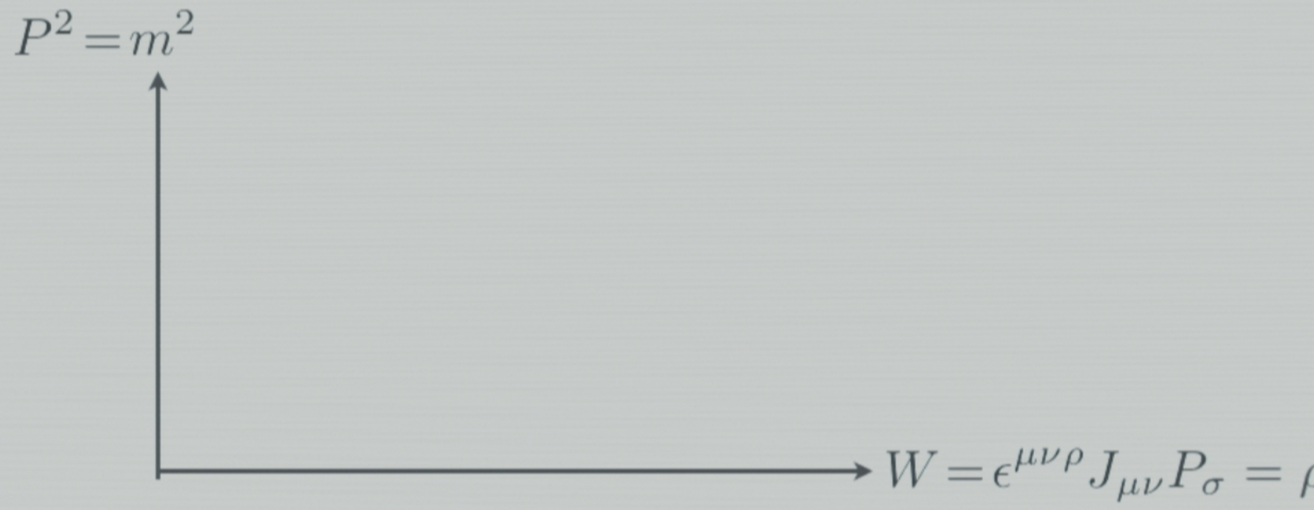


The Spin-Menu in 3D

One-dimensional little group
$\Rightarrow$ only single-state irreps



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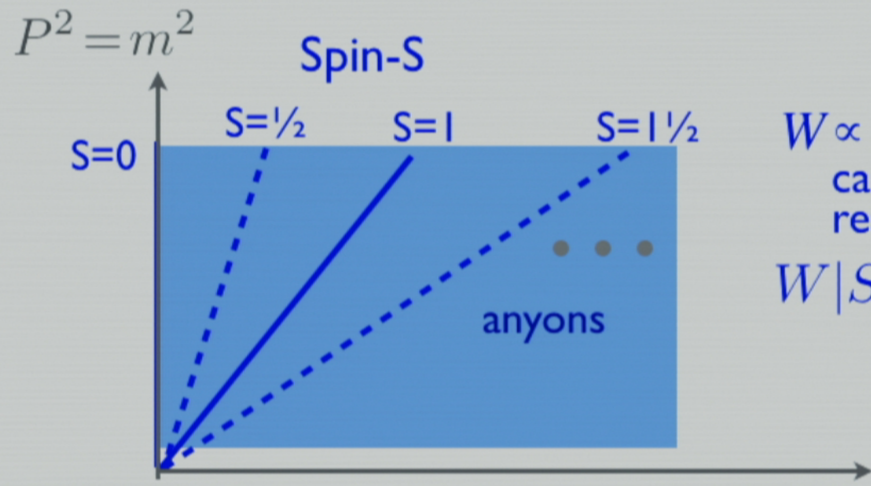

$W = \epsilon^{\mu\nu\rho} J_{\mu\nu} P_\sigma = \rho$

$W \propto$ rotation
can take ***any***
real eigenvalue

$W|S\rangle = mS|S\rangle$


Generalizing "spin" to massless particles naturally → CSP
... with fixed helicity as a degenerate special case.
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Outline

1. Long-Range Forces and Inevitable Symmetry

2. The Last Massless Particle

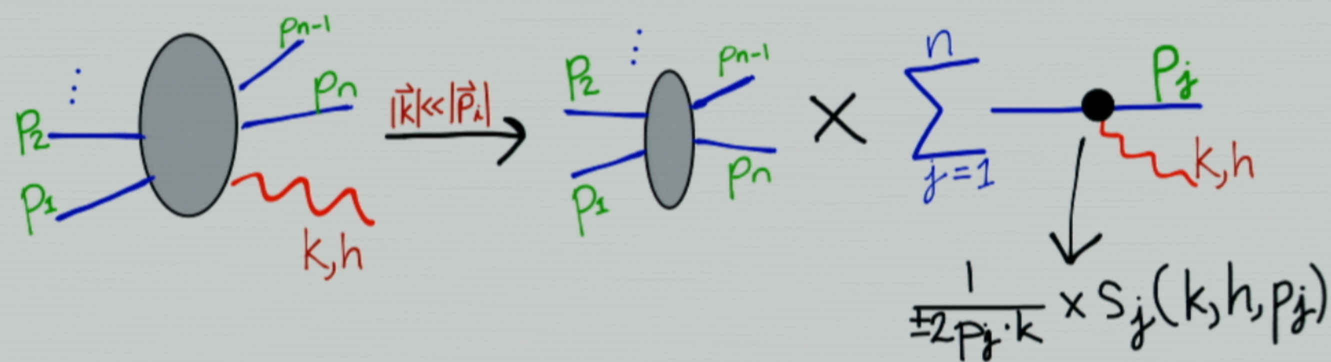
3. How can CSPs interact?
   - Soft emission
   - Scalar (h=0) correspondence
   - A Local Gauge Theory

4. CSP Physics and The Correspondence Limit

Continuous Spin and the
consequences of QM + Relativity

For soft (low-momentum) particle:

unitary ⇒ emission from external legs dominates



Continuous Spin and the consequences of QM + Relativity

For soft (low-momentum) particle:

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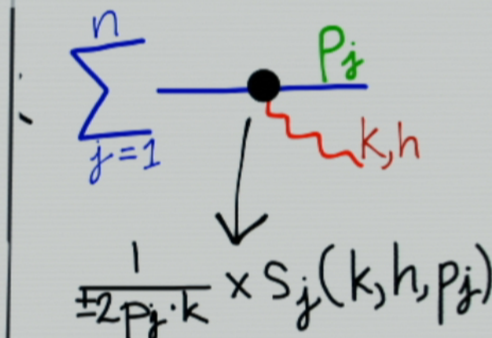
Soft factor must encode little group transformation but can only depend on very limited data

⇒ tightly constrained

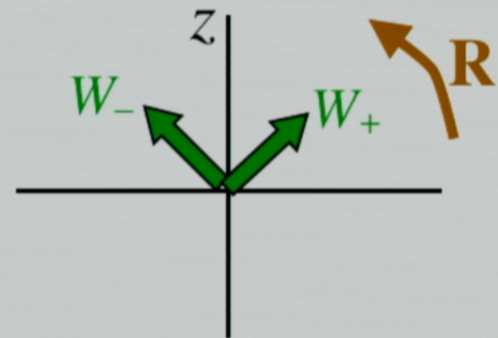


Lorentz-covariance: Λ[amplitude] = Λ[prod. of states]

Little Group: W[soft factor s_j*] = W[state* $|k, h\rangle$*]*

A Useful Result: Representing CSP States as Functions

Can think of massless Little Group as translation/ rephasing on a complex z-plane ($z = |z|\, e^{i\theta}$)



Functions $\tilde{J}_h(\rho z) \equiv J_h(\rho|z|)e^{-ih\theta}$

transform like CSP states under Λ_{LG}

Finding a soft factor $s(k,h,p)$ amounts to finding a $z(k,p)$ that transforms appropriately…

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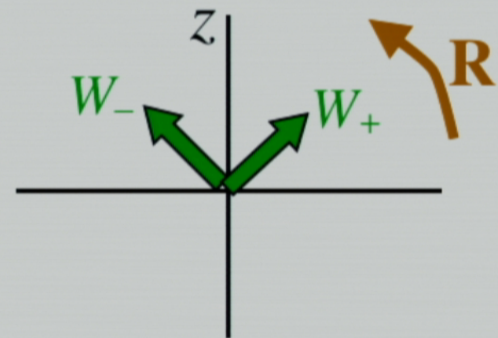

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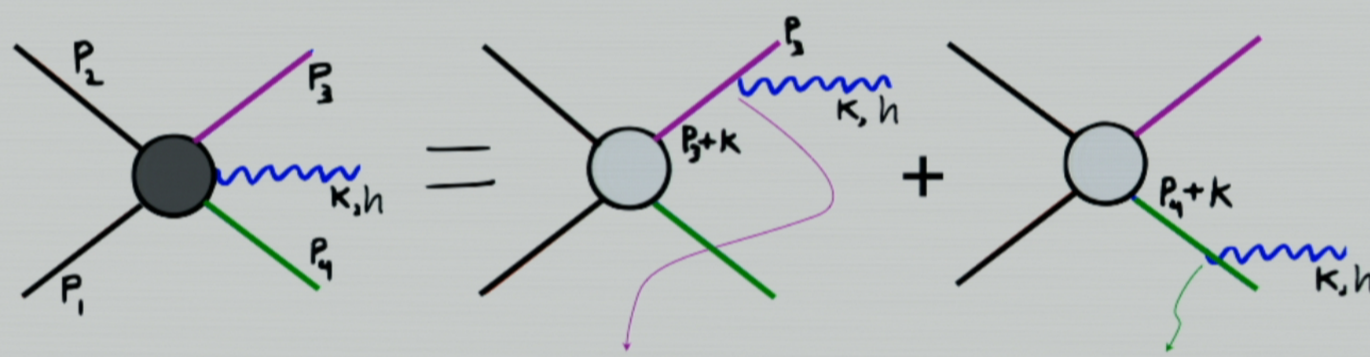
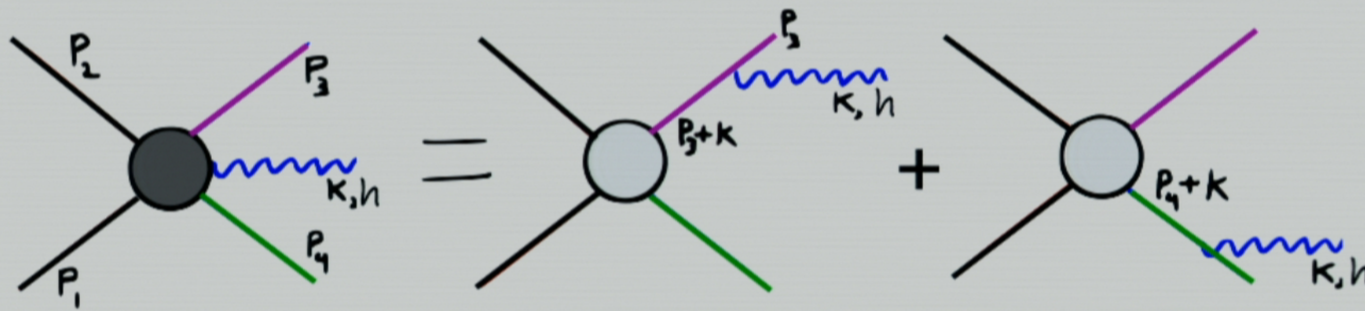
Building covariant amplitudes (simple example)

– four-scalar coupling
– both outgoing scalars interact with CSP (incoming do not)



$$\mathcal{A}_h = \lambda \left[\frac{1}{(p_3+k)^2+i\epsilon} \cdot a_3 \tilde{J}_h(\rho z_3) + \frac{1}{(p_4+k)^2+i\epsilon} \cdot a_4 \tilde{J}_h(\rho z_4) \right]$$

Emission cross-sections are scalar-like in small-ρ limit!



$$\sum_h |\mathcal{A}_h|^2 =$$

$$|\lambda|^2 \left(\frac{|a_3|^2}{((p_3+k)^2)^2} + \frac{|a_4|^2}{((p_4+k)^2)^2} + \frac{2Re[a_3 a_4^*] J_0(\rho|z_3 - z_4|)}{(p_3+k)^2 (p_4+k)^2} \right)$$

ρz = correspondence parameter

(recover scalar result when $\rho z \rightarrow 0$)

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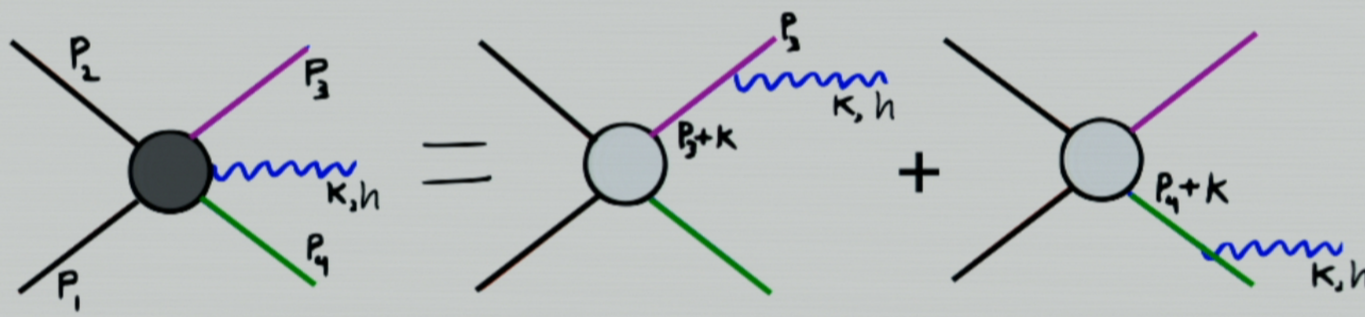

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ρz = <u>correspondence parameter</u>

(recover scalar result when $\rho z \to 0$)


Correspondence parameter z:
$z(k,p) \equiv \frac{\epsilon_+ \cdot p}{k \cdot p}$
(with small-angle corrections)
$|z| \sim v/|\mathbf{k}|$
matter velocity
CSP energy
k (CSP momentum)
p (matter momentum)
θ
Correspondence limit $\rho z \ll 1$ is the limit of
high-energy radiation and/or
non-relativistic emitters.
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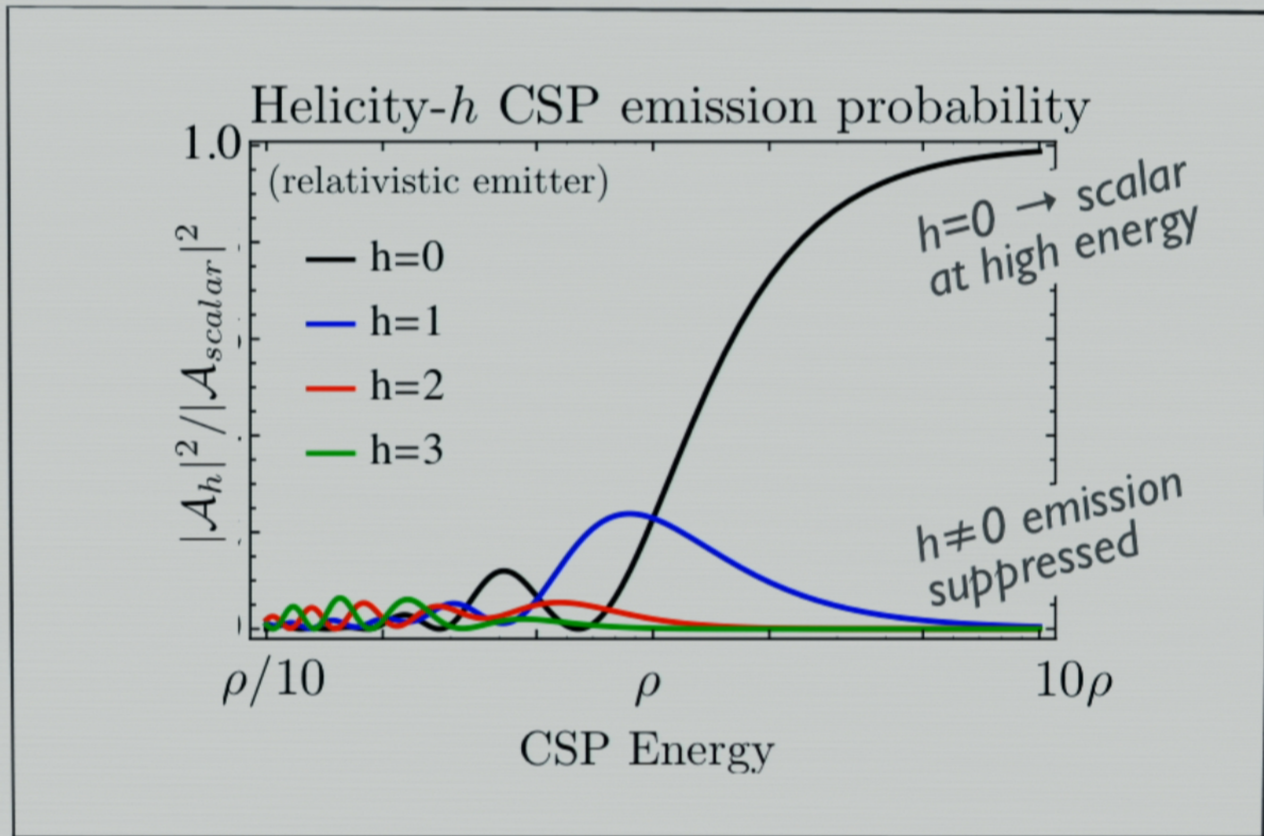
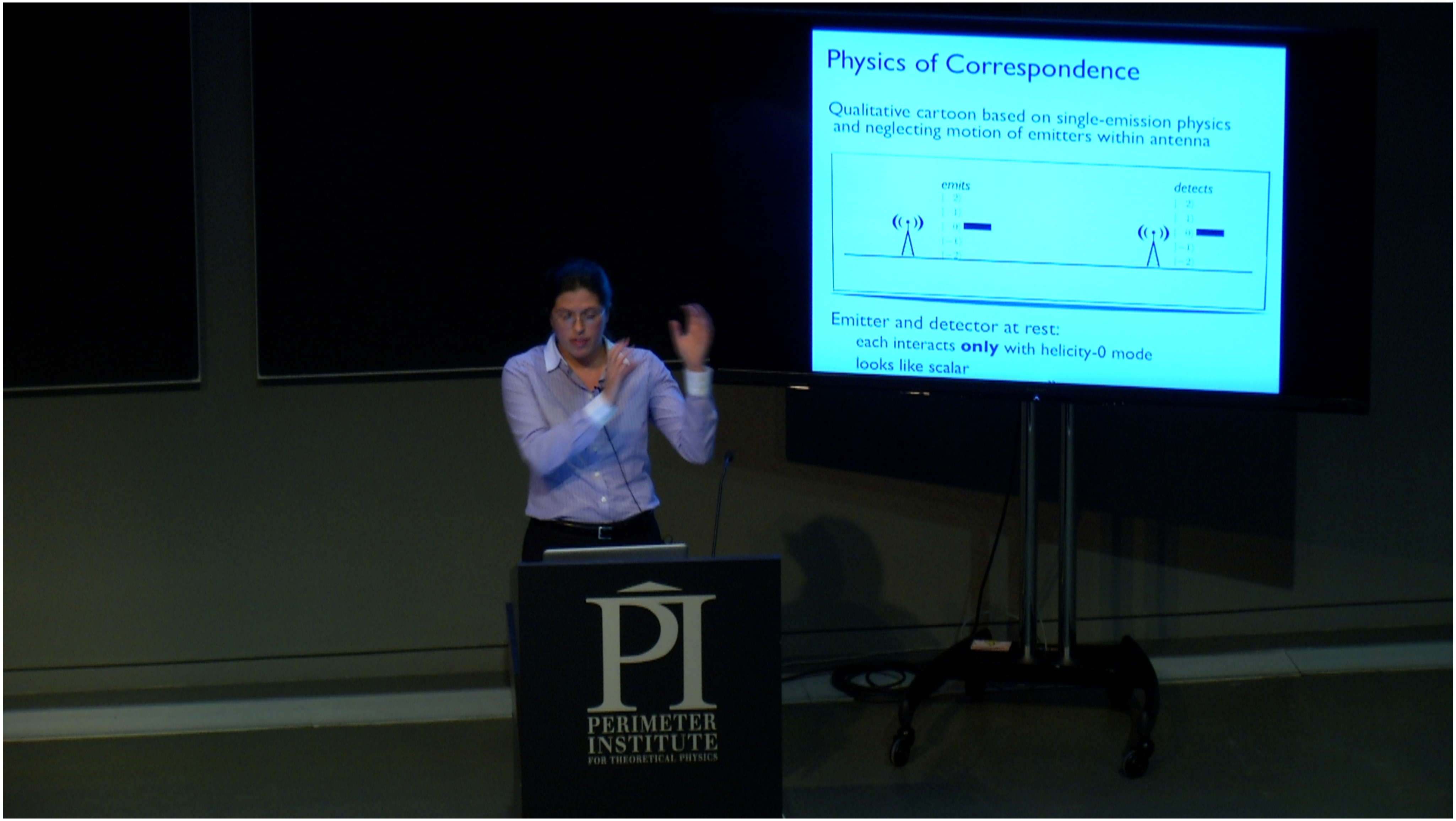
Correspondence in Helicity-h Amplitudes



$$|J_h(\tfrac{\rho}{E})|^2 \approx \tfrac{1}{h!^2}\left(\tfrac{\rho}{2E}\right)^{2h} + \dots \qquad \text{(large } E\text{)}$$


Physics of Correspondence
Qualitative cartoon based on single-emission physics and neglecting motion of emitters within antenna
emits
detects
Emitter and detector at rest:
each interacts only with helicity-0 mode
looks like scalar
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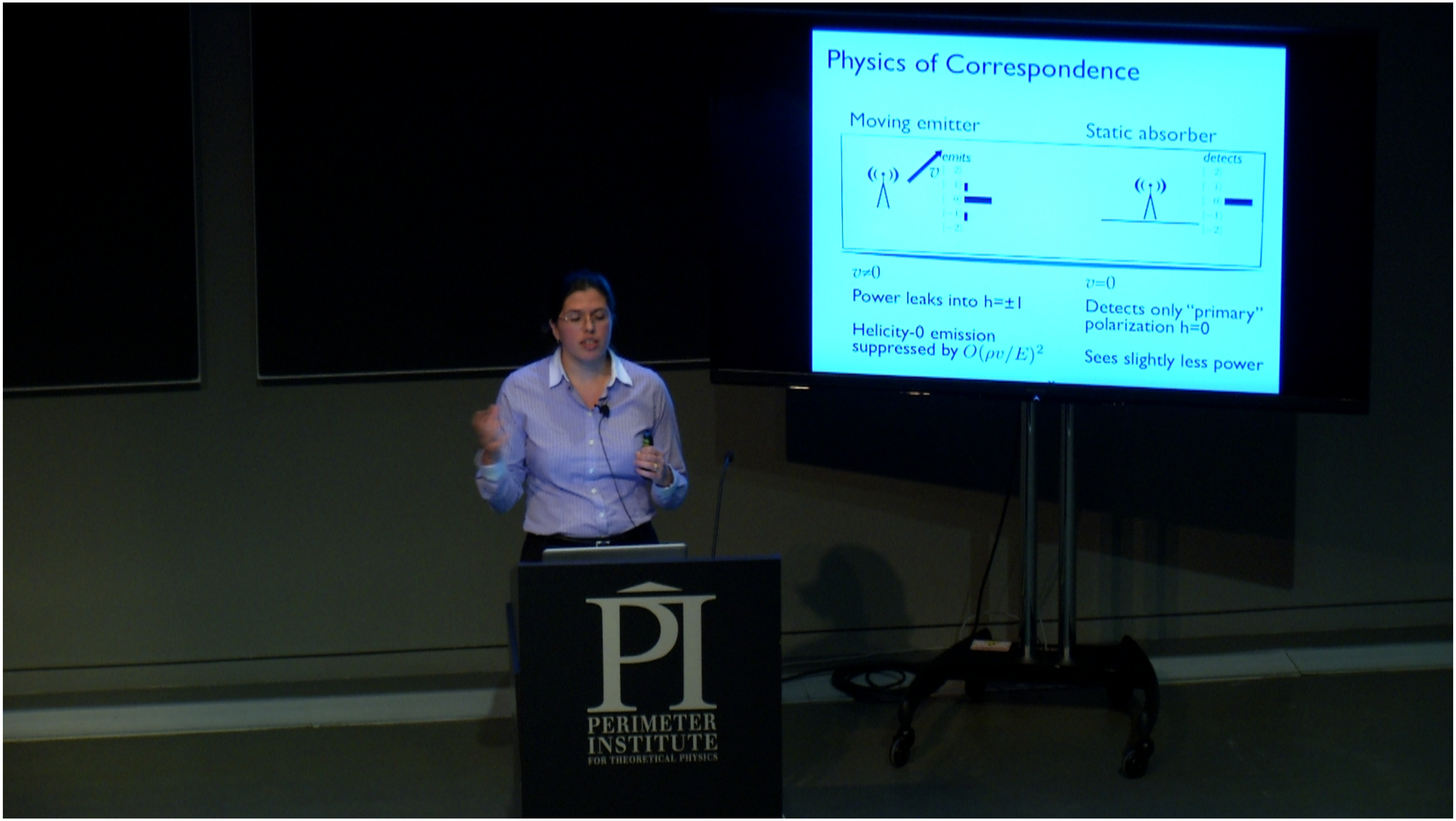
Physics of Correspondence
Moving emitter
Static absorber
emits
detects
v
$v \neq 0$
Power leaks into h=±1
Helicity-0 emission suppressed by $O(\rho v/E)^2$
$v=0$
Detects only "primary" polarization h=0
Sees slightly less power
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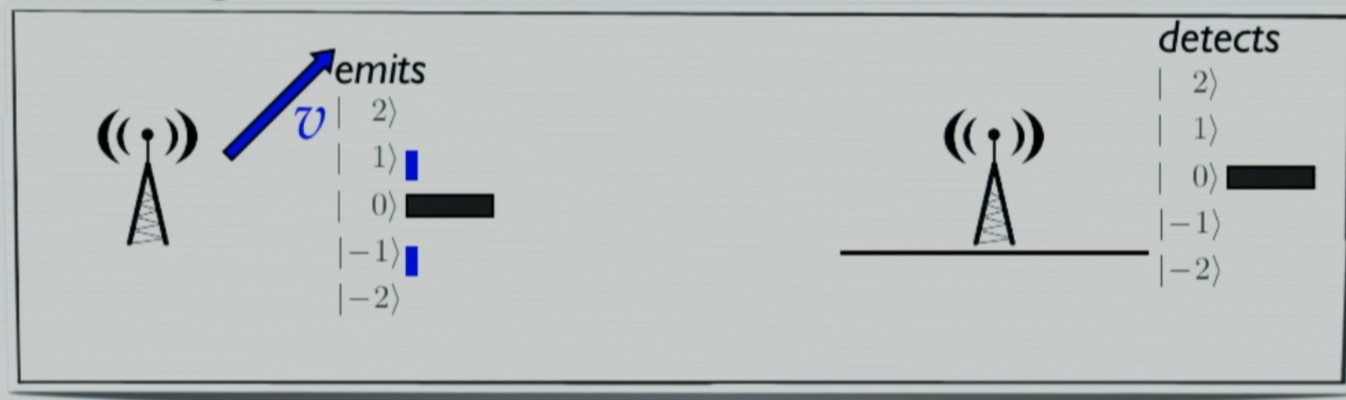
Physics of Correspondence

Moving emitter | Static absorber



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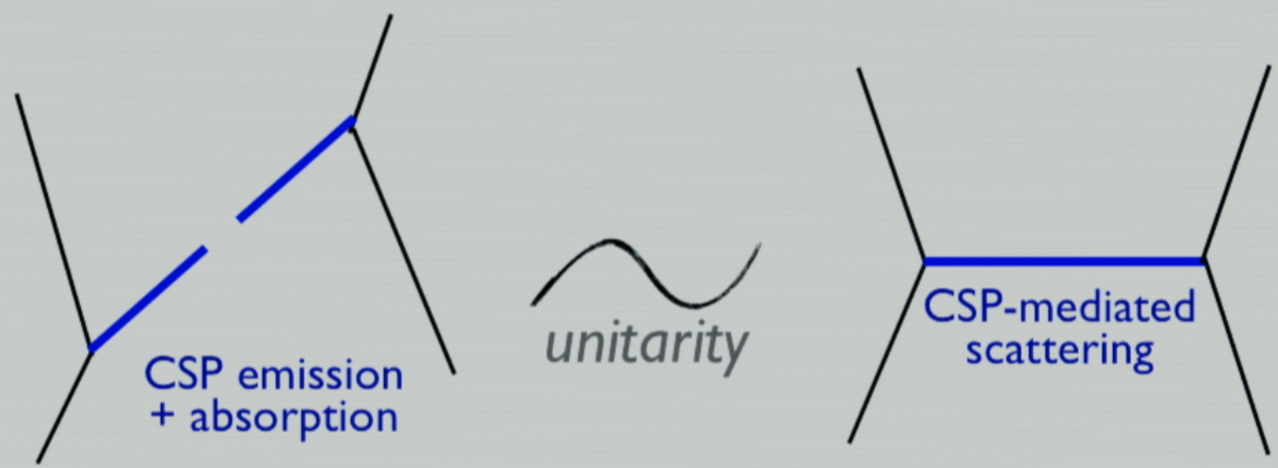
Correspondence and Force-Laws



Summary: A series of small miracles

0) Lorentz invariance and unitarity allow simple (and highly constrained) single-emission amplitudes:

$$s(k, h, p_i) \propto \tilde{J}_h(\rho z_i)$$

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[higher-point ansatz amplitudes have same features]
– Soon: from a small variation on this soft factor, recover gauge- and GR-like high-energy behavior (instead of scalar)
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- Soon: from a small variation on this soft factor, recover gauge- and GR-like high-energy behavior (instead of scalar)
- But first: another look at CSP kinematics, interactions, and correspondence from field theory

Towards the classical limit

Classical Effects
- Force-laws
- Radiation by macroscopic bodies

Quantum Consisten
- Scattering amplitude
- Particles
- Unitarity constraint

Can we build fields whose propagating degrees of freedom are CSPs?

To encode all helicity-h, need multiple tensors

$$\varphi^{(0)}(x) + \quad \varphi^{(1)}_{\mu}(x) + \quad \varphi^{(2)}_{\mu\nu}(x) + \ldots$$

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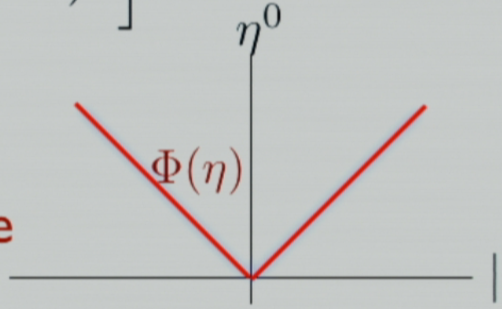
$$\Phi(\eta, x) \equiv \varphi^{(0)}(x) + \eta^{\mu}\varphi^{(1)}_{\mu}(x) + \eta^{\mu}\eta^{\nu}\varphi^{(2)}_{\mu\nu}(x) + \ldots$$

η-Geometry In Action

$$S = \int d^4x d^4\eta \delta'(\eta^2) \left[(\partial_x \Phi)^2 - \frac{\eta^2}{2} (\Delta\Phi)^2 \right]$$

$$\Delta = \partial_\eta . \partial_x + \kappa$$

defined on neighborhood of null-η cone



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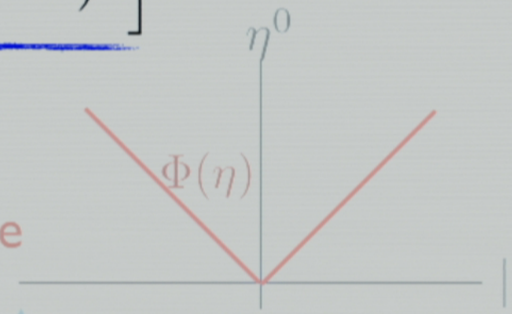

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similar form to QED $-(\partial_\mu A_\nu)^2 \quad +(\partial.A)^2$

Physical degrees of freedom live on *η-space plane*

– geometry realizes Little Group E_2

– κ≠0: action for CSPs of all ρ

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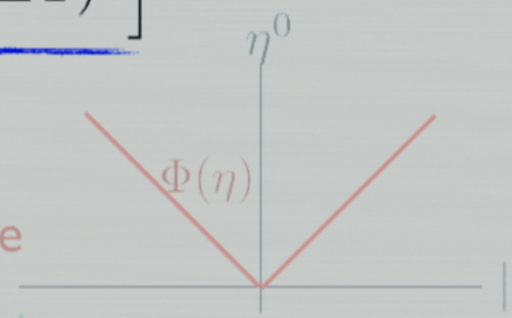

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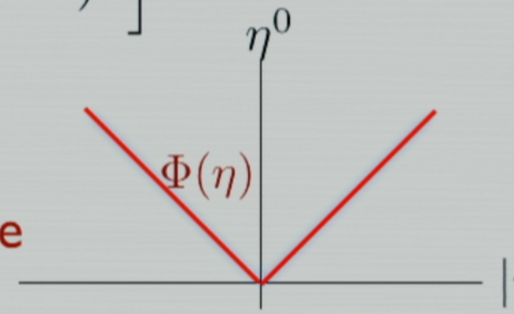

CSP Field Interactions – More correspondenc

$$S = \int d^4x d^4\eta \delta'(\eta^2) \left[(\partial_x \Phi)^2 - \frac{\eta^2}{2} (\Delta\Phi)^2 + J(\eta, x)\Phi \right]$$

where J satisfies a continuity condition

Component equations of motion:

$$-\Box_x \phi + \rho\, \partial \cdot A = J^{(0)}$$

$$\Box_x A_\mu - \partial_\mu \partial \cdot A - \rho\, \partial^\nu h_{\mu\nu} = J^{(1)}_\mu$$

$$\cdots$$

CSP Field Theory Reinforces:

New particle type consistent with Lorentz symmetry

- Free propagation of CSPs from field theory

Interactions compatible with Lorentz+Unitarity

- Consistent, gauge-invariant coupling to background currents

CSP Field Theory: Matter-Interactions

Are there matter-CSP couplings where current "conservation" follows from matter e.o.m.? (free and interacting)

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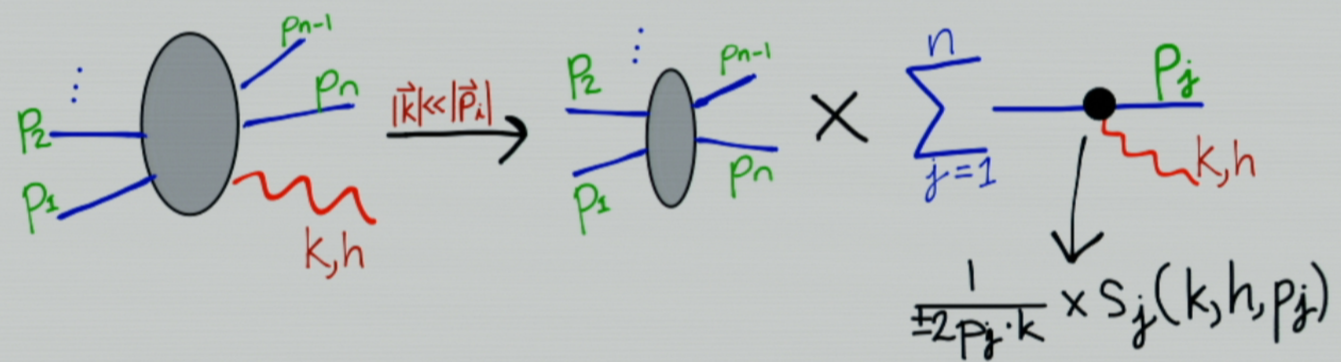
- Work in progress
- Existence of matter-emission amplitudes suggest that currents should also exist
- Potentially revealing – this is where "bottom-up" construction of Yang-Mills or GR reveals the need for self-interactions

interaction with conserved vector/tensor currents hint at gauge/gravity-like structure…

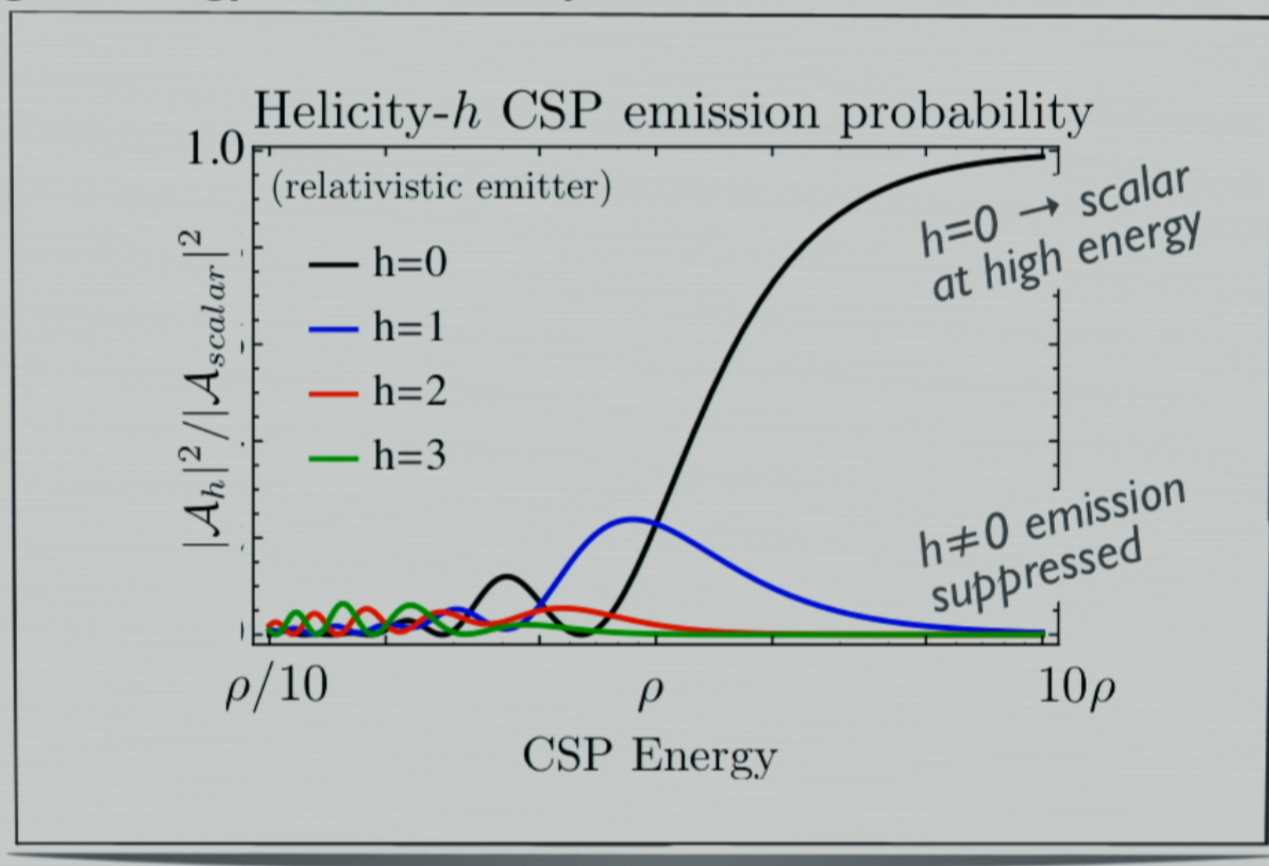
Recall QM + Relativity ⇒

unique consistent form for CSP interactions:



$$s(k,h,p) = J_h(\rho|z|)e^{-ih\arg(z)} \equiv \tilde{J}_h(\rho z)$$

Cross-sections & amplitudes approach scalar theory in high-energy/low-velocity limit



$$|J_h(\frac{\rho}{E})|^2 \approx \frac{1}{h!^2}\left(\frac{\rho}{2E}\right)^{2h} + \dots \qquad \text{(large } E\text{)}$$

Gauge Correspondence

$$s(k,h,p_i) = q_i \frac{p_i.k}{\rho} \tilde{J}_h(\rho z_i)$$

Scalar ⇒ Lorent
symmetry not
changed

Why didn't we consider this?

High-energy growth ⇒ violates perturbative unitarity

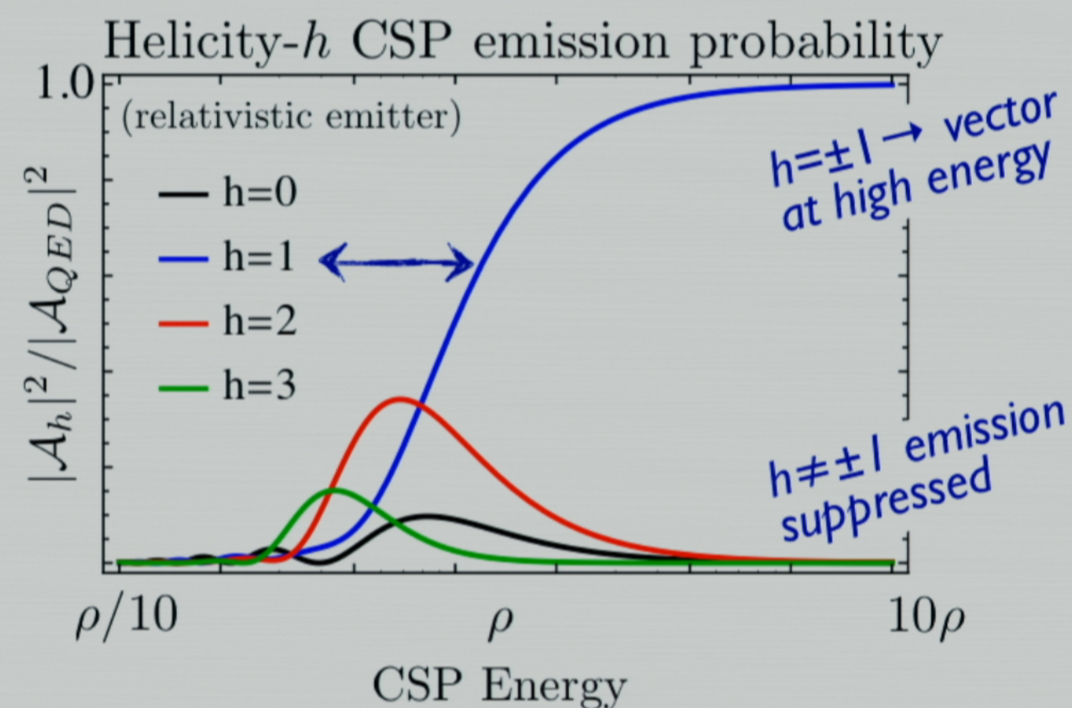
$$\sigma \lesssim 4\pi/E_{cm}^2$$

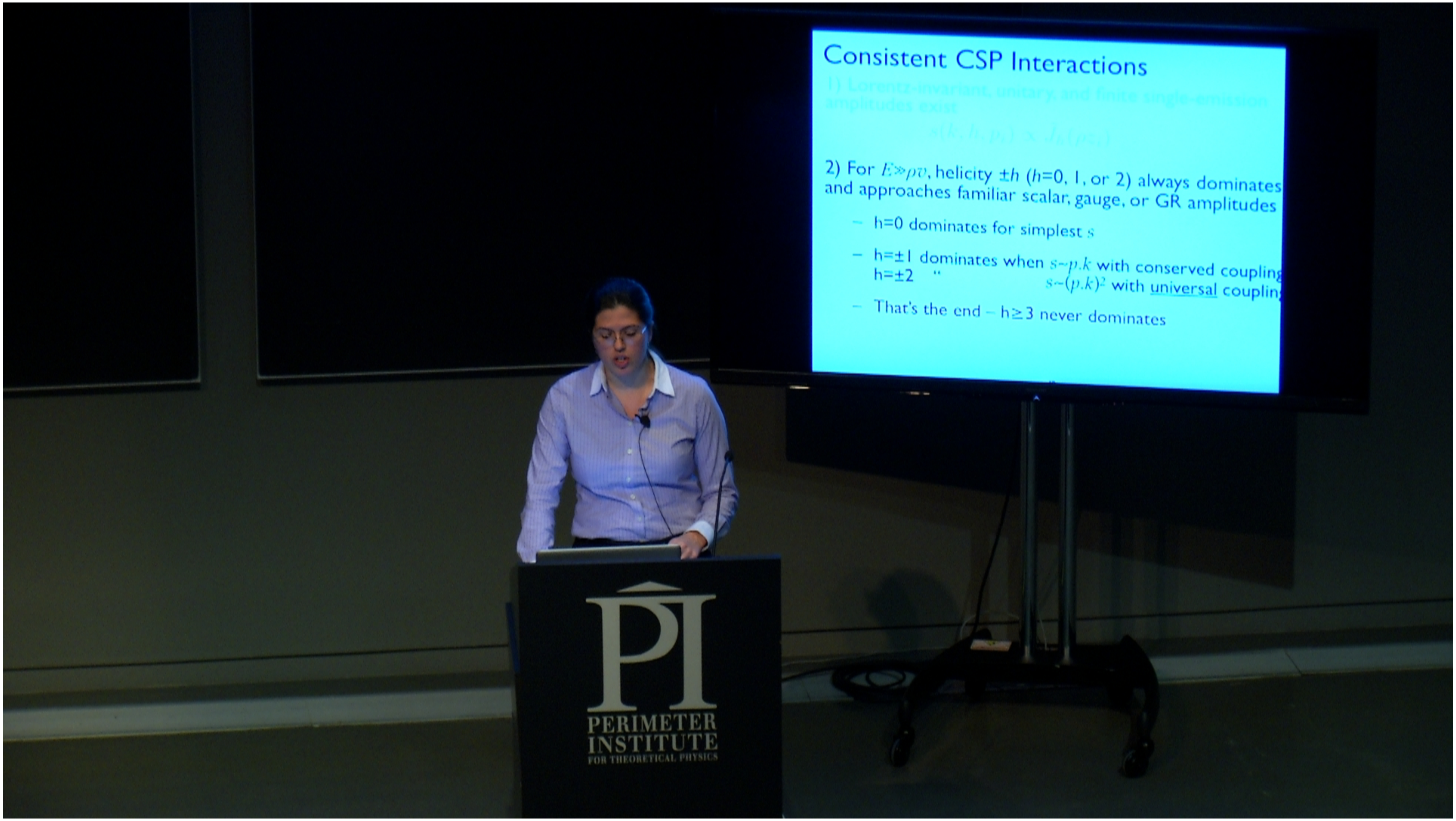
at E_{cm}~ρ/q_i – UV cutoff

Gauge Correspondence

$$s(k, h, p_i) = q_i \frac{p_i.k}{\rho} \tilde{J}_h(\rho z_i)$$

with q_i conserved




Consistent CSP Interactions
2) For $E \gg \rho v$, helicity $\pm h$ (h=0, 1, or 2) always dominates
and approaches familiar scalar, gauge, or GR amplitudes
– h=0 dominates for simplest s
– h=±1 dominates when $s \sim p.k$ with conserved coupling
h=±2 " $s \sim (p.k)^2$ with universal couplin
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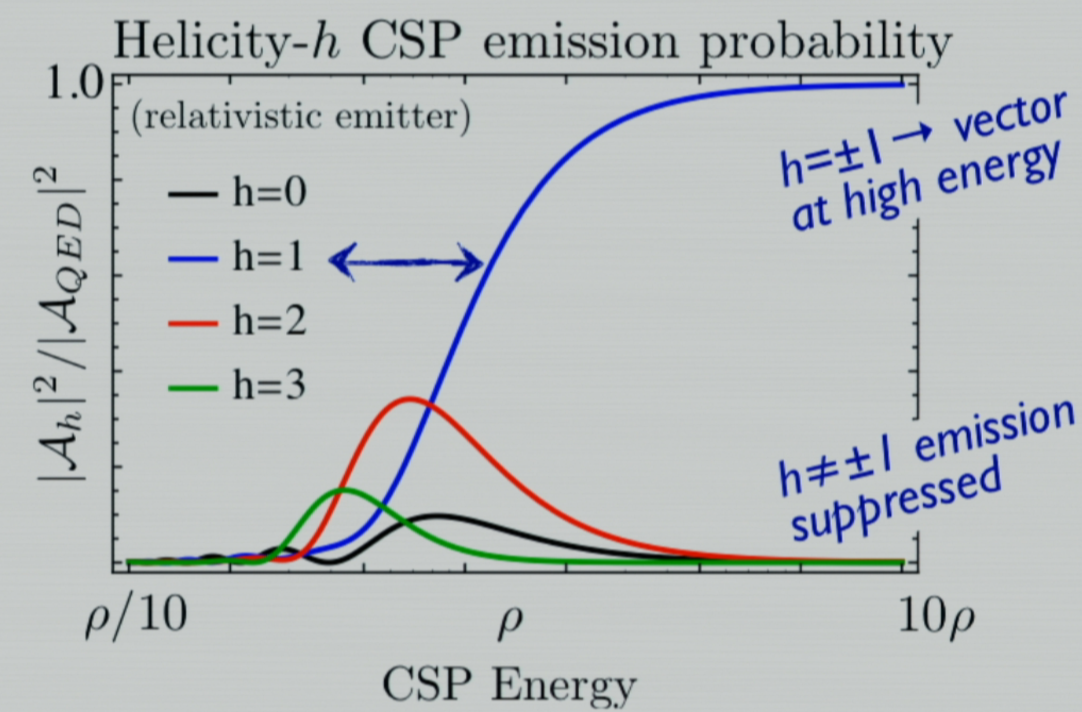

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an experimental question:

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are they helicity-1 and helicity-2, or merely helicity-1-like and helicity-2-like (with small ρ)?

Possible tests:

- Modified radiation patterns (esp. at long wavelength)
- Modified force-laws & velocity-dependence
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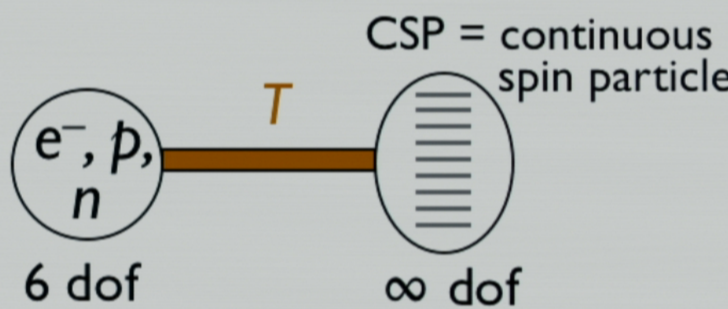
- Changes to thermodynamics
  - early universe
  - well-insulated systems

Thermodynamic catastrophe?

Thermal equilibrium ⇒ equipartition



Once equilibrated, thermodynamics ***completely*** *dominated by CSP*

[Wigner '65]

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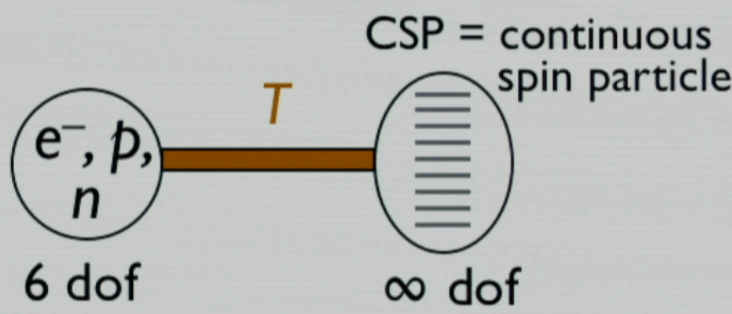

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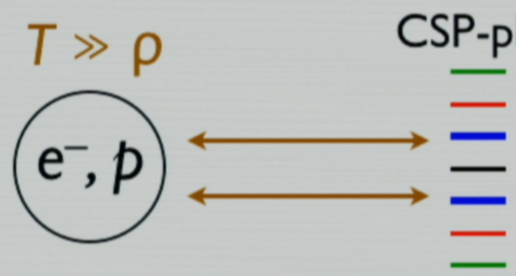
[Wigner '65]

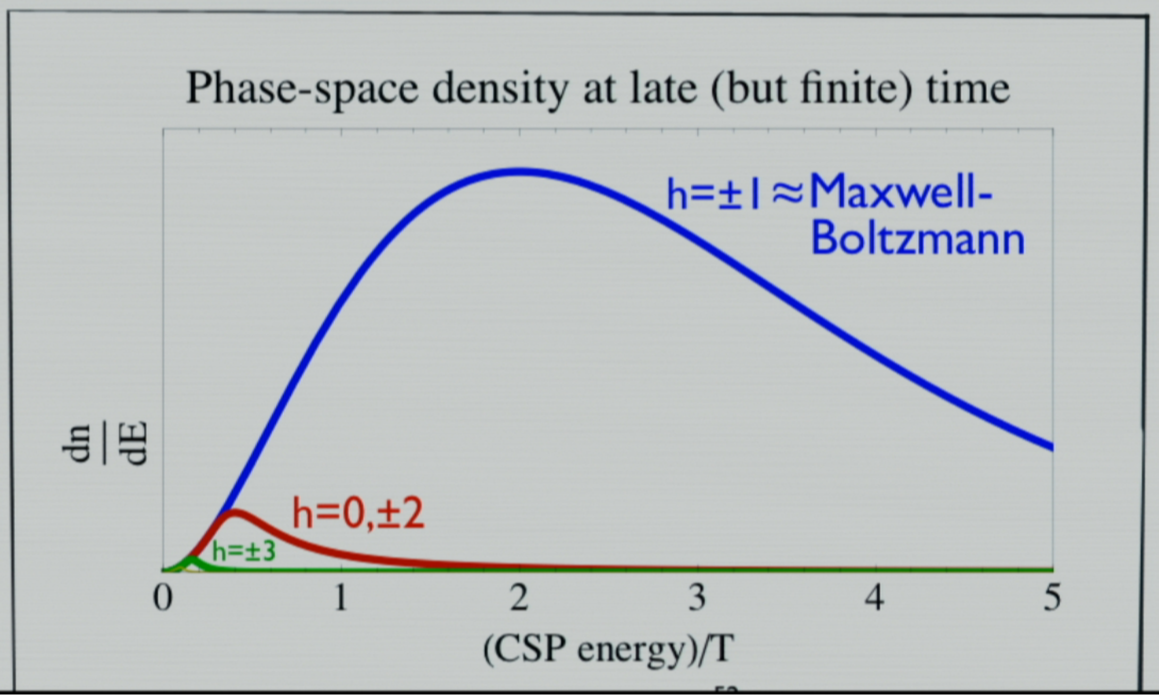
But this picture assumes that all CSP degrees of freedom thermalize on relevant time-scales…

Partial thermodynamic equilibrium



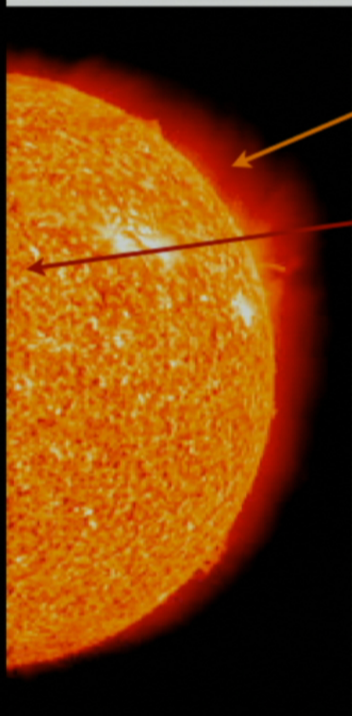
h=±1 modes equilibrate rapidly

other modes' equilibration time $\sim\tau\ (T/\rho)^2$ or longer



Phase-space densi
dn/dE
h=0,±2
h=±3
0
1
2
(CS

Solar Cooling as a Test of The Photon Spin-Scal



Luminosity ~ 10^{34} erg/s

Power$_{(brem)}$ ~ 10^{59} erg/s ≫ Lumi

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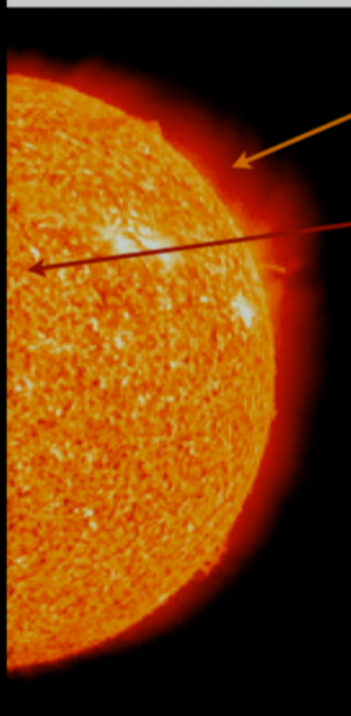

Luminosity ~ 10^{34} erg/s

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If *one* h≠1 CSP was brem'd per 10^{26} γ's
and escaped sun, luminosity and stellar
evolution would change by O(10%).

$$\rho^2 \lesssim 10^{-26} m_e T \sim (10^{-8}\mathrm{eV})^2$$

$$\rho^{-1} \gtrsim 10\mathrm{m}$$

[analogous to light-axion constrain

Cooler stars ⇒ few-10x stronger bound on ρ

Where else to look?

For CSP photon: stellar limit $\rho^{-1} \gtrsim 10\mathrm{m}$ $\Rightarrow$ radio-emission and macroscopic force laws as experimental frontier

For CSP graviton: thermodynamics is very weak constraint! But force-law modifications are tightly constrained.

Hubble-scale effects theoretically interesting

Very different physics from PPN, photon/graviton mass — **limiting factor** in search for non-zero ρ is our theoretical understanding

Summary

- Generic massless particle (CSP) compatible with relativity
  - <u>all</u> integer* helicities mix under boosts
  - characterized by a spin-scale ρ

- Interaction consistency checks
  - Consistent & finite amplitudes
  - Thermodynamics
  - Local gauge theory

- Recovers familiar helicity-0, 1, and 2 physics in high-energy limit ($E \gg \rho$)


– characterized b
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Is ρ=0 Gauge + Gravity Inevitable?

- Doesn't seem so inevitable – there's a more generic possibility

Is ρ=0 Gauge + Gravity Inevitable?

- ρ=0 doesn't seem so inevitable!

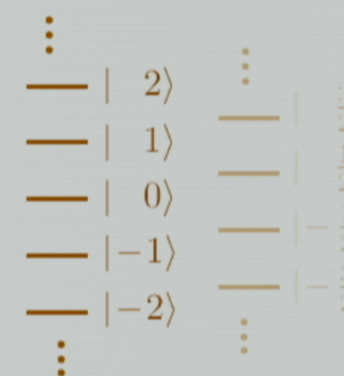
- The essential physics now seems ***even more*** inevitable

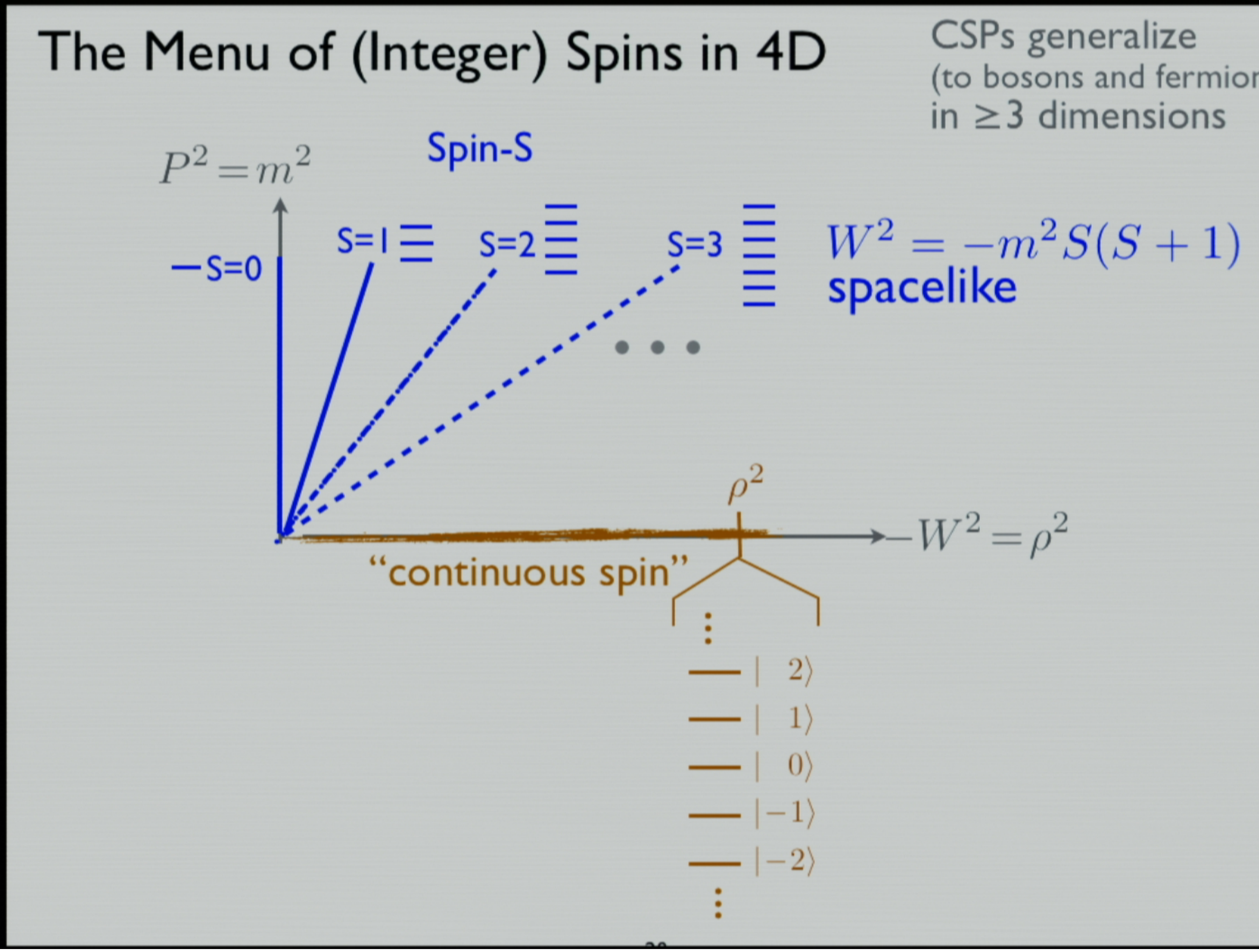
  - CSP physics is essentially scalar-, gauge-, or GR-like

Momentum-Preserving Lorentz Generators

Generators = 3 components of W^μ
work as in massive case.

- Helicity-rotation $\mathbf{R} = \vec{\mathbf{J}}.\hat{p}$
  eigenstates $\mathbf{R}|h\rangle = h|h\rangle$ h=(½)-integer
- 2 x less familiar generators (transverse rot+boost)




The Menu of (Integer) Spins in 4D
CSPs generalize
(to bosons and fermion
in ≥3 dimensions
Spin-S
$P^2 = m^2$
S=0
S=1
S=2
S=3
$W^2 = -m^2 S(S+1)$
spacelike
ρ^2
$-W^2 = \rho^2$
"continuous spin"
$|\ 2\rangle$
$|\ 1\rangle$
$|\ 0\rangle$
$|-1\rangle$
$|-2\rangle$