

Title: Standard Model & EDM, g-2

Speakers: Jesse Thaler

Collection: School on Table-Top Experiments for Fundamental Physics

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The Standard Model

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Principles

P



## Principles

- QM  $\rightarrow$  Unitarity
- Lorentz inv.  $\Rightarrow$  Mass & Spin
- CPT / Spin-statistics  $\Rightarrow$   $\begin{matrix} \text{integer spin} \Leftrightarrow \text{boson} \\ \text{half-integer spin} \Leftrightarrow \text{fermion} \end{matrix}$
- Locality / Causality  $\Rightarrow$  forces  $\leftrightarrow$  fields / prop.

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- ...
- ? Global Symmetries  $\leftrightarrow$  Conservation Law
- ? Supersymmetries

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- ...
- ? Global Symmetries  $\leftrightarrow$  Conservation Laws
- ? Supersymmetries
- ? Naturalness

## Paradigms

## Principles

- QM  $\Rightarrow$  Unitarity
- Lorentz  $\Rightarrow$  Mass & Spin
- (P)  $\Rightarrow$  Fermi-Dirac statistics  $\Rightarrow$  integer spin  $\Leftrightarrow$  bosons  
half-integer spin  $\Leftrightarrow$  fermions
- $\Rightarrow$  forces  $\Leftrightarrow$  fields / propagators
- $\Leftrightarrow$  Conservation Laws

## Paradigms

- Spontaneous Sym. Breaking  $\Rightarrow$  Higgs Mech.
- Confinement / Asymptotic Freedom  $\Leftrightarrow$  QCD
- Accidental symmetries  $\rightarrow$  B/L number
- ? Neutrino Masses  $\Leftrightarrow$  Majorana vs. Dirac
- ? Dark Matter  $\Rightarrow$  Many other lectures!
- ? Baryogenesis
- ? Unification
- ? Inflation

## Principles Have Consequences

- Weakly coupled  $\Rightarrow$  particle descriptor
- Lorentz/Poincaré  $\Rightarrow$  particles have well-defined mass

★ Massive particles



Boost

$\Rightarrow$

$$SO(3) \cong SU(2)$$

Spin!

Spin: 0    $\frac{1}{2}$    1    $\frac{3}{2}$    2    $\frac{5}{2}$    ...

$\Rightarrow$  Can't be fundamental

Spin-1  $w^{\pm}/Z$

$\hookrightarrow$  Higgs mech.

Spin- $\frac{3}{2}$  ( $SU(2)_R$ )

$\hookrightarrow$  super-Higgs mechanism

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Spin!

Spin: 0    $\frac{1}{2}$    1    $\frac{3}{2}$    2    $\frac{5}{2}$    ...   ★ Mass



4 of these  
(Higgs multiplet)

$\Rightarrow$  Can't be fundamental!

Spin-1  $w^{\pm}/Z$

$\hookrightarrow$  Higgs mech.

Spin-3/2 (Gravitino)

$\hookrightarrow$  Super-Higgs mechanism

Spin: 0    $\frac{1}{2}$    1    $\frac{3}{2}$    2    $\frac{5}{2}$  ...

(fund. mass)

↓  
4 of these  
(Higgs) multiplet

⇨ Can't be fundamental

Spin-1  $w^{\pm}/Z$   
↳ Higgs mech.

Spin- $\frac{3}{2}$   $(\psi_{\pm})$   
↳ Super-Higgs mechanism

\* Massless particles, no rest frame



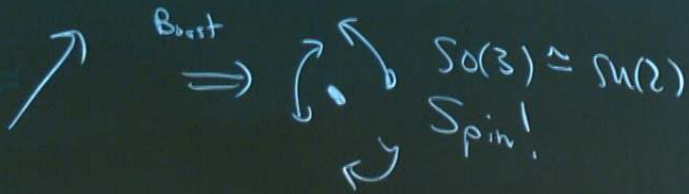
Boost  
⇒



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 $\hookrightarrow$  Higgs mech.

Spin- $\frac{3}{2}$   $(\psi_{\pm 1/2})$   
 $\hookrightarrow$  Super-Higgs mechanism

Spin: 0  $\frac{1}{2}$  1  $\frac{3}{2}$  2  $\frac{5}{2}$  ...

↓

4 of these (Higgs multiplet)

⇒ Can't be fundamental

Spin-1  $\omega^{\pm 1/2}$   
 ↳ Higgs mech.  
 Spin- $\frac{3}{2}$   $(SU(2)_A)$   
 ↳ Super-Higgs mechanism

\* Massless particles, no rest frame

Boost ⇒

Helicity: 0  $\frac{1}{2}$  1  $\frac{3}{2}$  2  $\frac{5}{2}$  ...

$SU(2) \simeq U(1)$   
 Helicity \* CSR

Spin: 0,  $\frac{1}{2}$ , 1,  $\frac{3}{2}$ , 2,  $\frac{5}{2}$ , ...

5 d.o.f.

4 of these  
(Higgs multiplet)

Can't be fundamental

Spin-1  $w^{\pm}/Z$   
↳ Higgs mech.

Spin- $\frac{3}{2}$  ( $SU(2)_1$ )  
↳ Super-Higgs mechanism

\* Massless particles, no rest frame

Boost  $\Rightarrow$

Helicity: 0,  $\frac{1}{2}$ , 1,  $\frac{3}{2}$ , 2,  $\frac{5}{2}$ , ...

$SO(2) \simeq U(1)$   
Helicity  $\star$  CSR

$\pm 2$  helicity

Spin: 0,  $\frac{1}{2}$ , 1,  $\frac{3}{2}$ , 2,  $\frac{5}{2}$ , ...

5 d.o.f. ↓

⇒ Can't be fundamental

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Spin- $\frac{3}{2}$   $(SU(2)_1)$   
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★ Massless particles, no rest frame

Boost ⇒

Helicity: 0,  $\frac{1}{2}$ , 1,  $\frac{3}{2}$ , 2,  $\frac{5}{2}$ , ...

±2 helicity

SO(2) ≈ U(1)  
 Helicity ↑ CSR

⇒ discontinuous massless limits  
 ⇒ no interactions

Massless in SM

$45 = 3 + 15$  spin- $\frac{1}{2}$  Weyl fermions

$15 = 6 + 3 + 3 + 2 + 1$

$12 = 1 + 3 + 8$  spin-1 bosons

Remarkably, this information

$\Rightarrow$  19 parameters (20 parameters)

Massive

Spin: 0    $\frac{1}{2}$    1    $\frac{3}{2}$     $\frac{5}{2}$

5 d.o.f.

$\Rightarrow$  Can't be fundamental

4 of these  
(Higgs multiplet)

Spin-1  $w^\pm / Z$

$\hookrightarrow$  Higgs mechanism

Spin- $\frac{3}{2}$  (SUSY)

$\hookrightarrow$  Super-Higgs

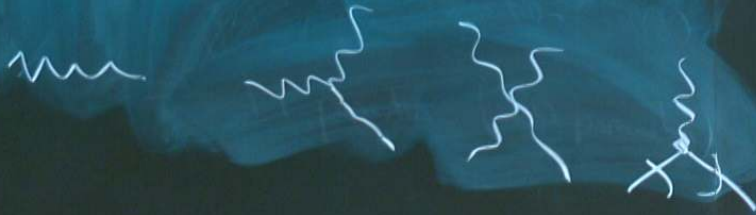
QM constraints on Massless particles

\* Massless Spin-2 plus unitarity ...

$\Rightarrow$

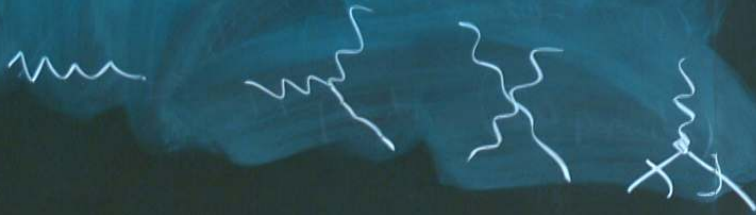
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 $\Rightarrow$  Einstein's gravity (!)

• Dictated by QM!



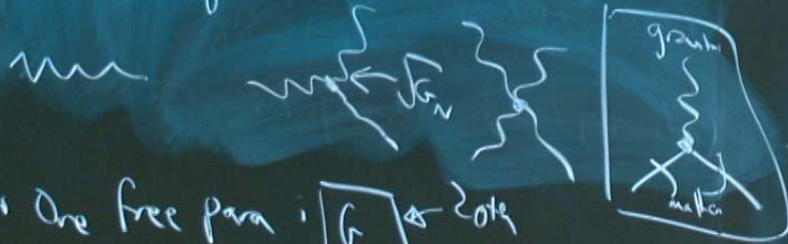
• One free para:  $G_N$

• Must couple to conserved  $T_{\mu\nu}$

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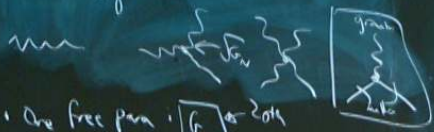
- One free para:  $\sqrt{\frac{G_N}{c^3}}$  & note
- Must couple to conserved  $T_{\mu\nu}$



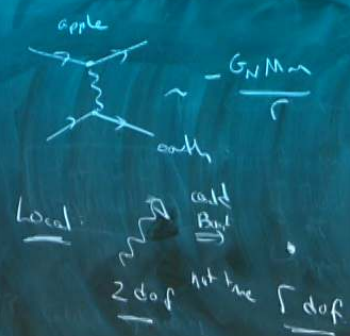
QM constraints on Massless Particles

\* massless spin-2 plus unitarity  
 => Einstein's gravity (!)

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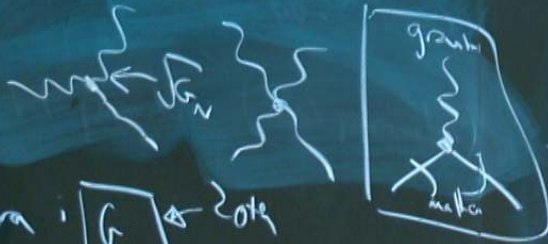
- One free para.  $\sqrt{\frac{G_N}{c^3}}$  or  $20\mu$
- Must couple to conserved  $T_{\mu\nu}$



# QM constraints on Massless particles

\* massless spin-2 plus unitarity  
 $\Rightarrow$  Einstein's gravity (!)

Dicted by QM!



- one free param.  $\sqrt{\frac{G_N}{M_{pl}^2}}$  & note
- Must couple to conserved  $T_{\mu\nu}$



Local  $\Rightarrow$  could be local  
 2 dof  $\Rightarrow$  not true  $\Rightarrow$  dof

# QM constraints on Massless particles

\* massless spin-2 plus unitarity  
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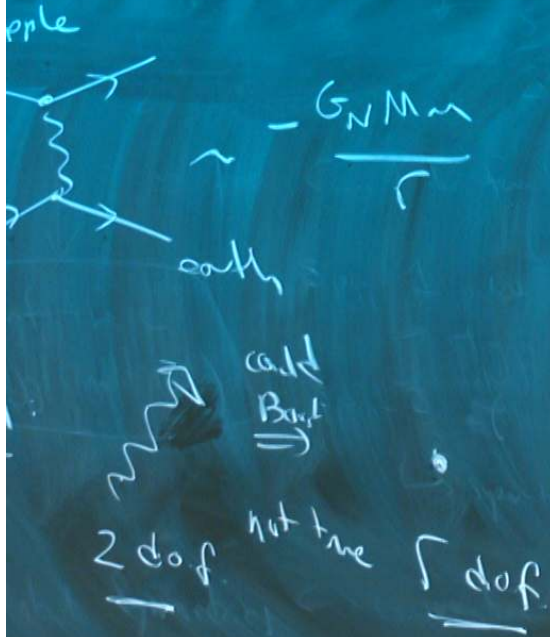
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- One free para.  $\sqrt{\frac{G_N}{M_{pl}}}$  2ote
- Must couple to conserved  $T_{\mu\nu}$



Local:  
 could be  
 2 dof  
 not true  $\sqrt{\text{dof}}$



★ Massless spin  $-3/2$

$\Rightarrow$  Supergravity ("N" is number of gravitons)  
 • Does not (yet) seem to describe nature



# QM constraints on Massless particles

\* Massless spin-1 plus unitarity

⇒ Gauge theories (!)

• Just 1 massless spin-1?

⇒ Maxwell's theory!

2 d.o.f

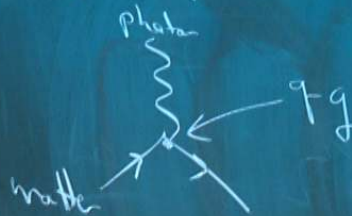
call boost

3 d.o.f

photon

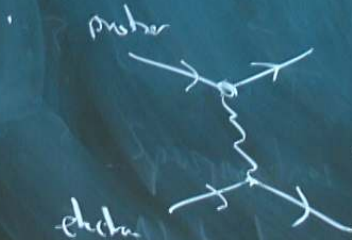
No self interactions allowed <sup>★</sup> kind of

• Must couple to conserved current



$q$  = charge

$g$  = coupling free para

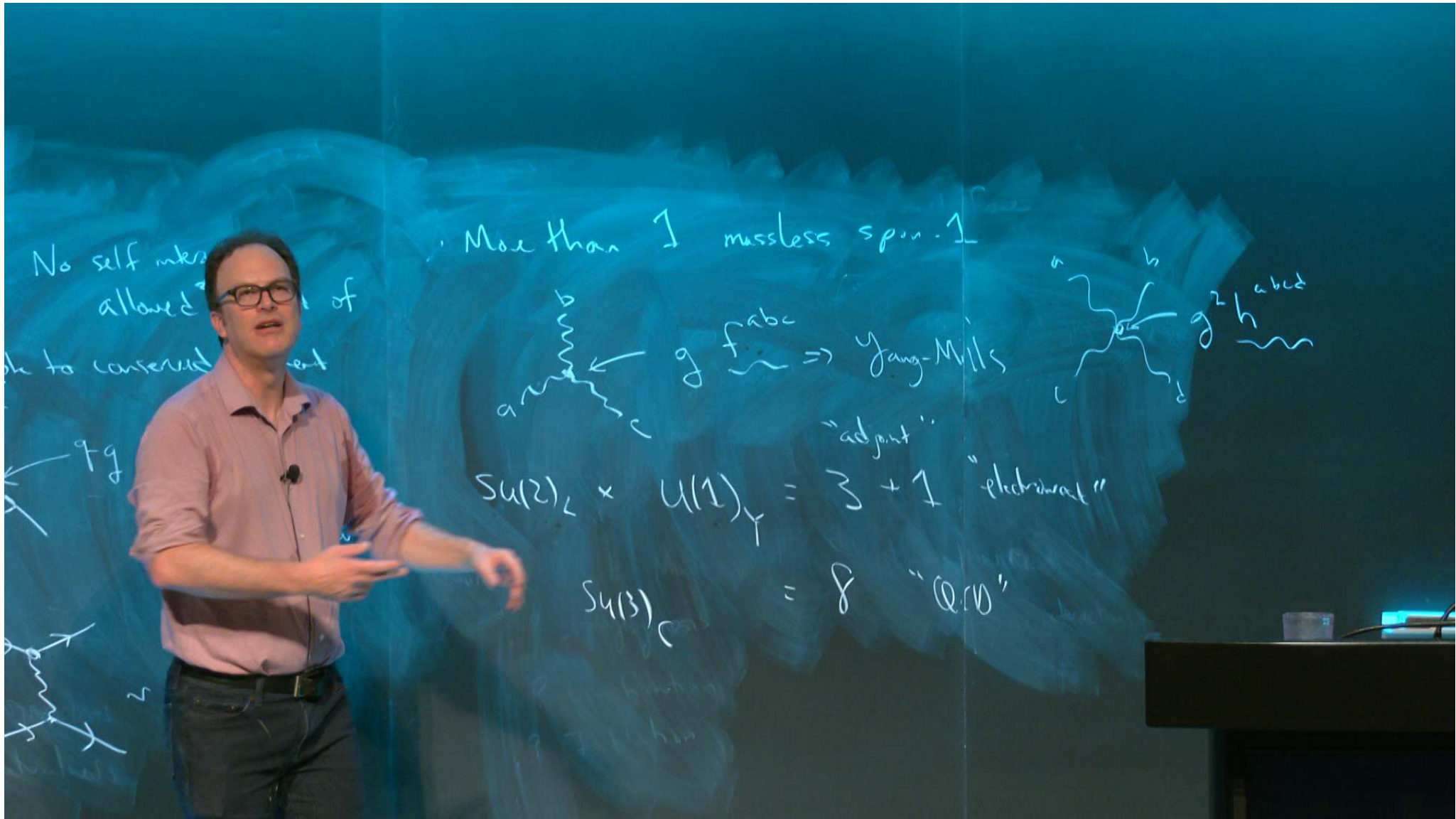


$\frac{d_{\mu\nu} Q q}{\omega}$

\* Massless

⇒

• Does



## QM constraints on Massless particles

\* massless spin- $\frac{1}{2}$  fermions

$\Rightarrow$  No constraints

charge under  $SU(3)_C \times SU(2)_L \times U(1)_Y$

Weyl fermions  $\Rightarrow$  left-hand particles  
right-hand antiparticles

Want reverse? Need another Weyl

\* massless spin-0

$\Rightarrow$  Radiatively unstable (?)

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SM next time

Ugliness  
of SM

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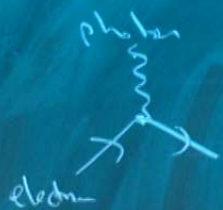
unstable (?)

## Building QED / GR

- massless spin-2 graviton ( $G_N$ )
- massless spin-1 photon ( $A_{EM}$ )
- 2 spin- $1/2$  Weyl fermions

	U(1) <sub>EM</sub> charge	
$e$	-1	massive Dirac fermion
$e^c$	+1	

Electron  $\longleftrightarrow$  <sup>anti</sup> positron



$\Rightarrow$  gives electric charge  
& magnetic coupling ( $g=2$ )



$\Rightarrow$  give running coupling  
& anomalies  $(g-2)_e$

Content C, D, T  $\Rightarrow$  no electric dipole moment

massless spin-0

$\Rightarrow$  Radiatively unstable (?)

SM next time

Ugliness of SM

Building Q

• massless

• massless

2 sp

e

e'