

# Exploring $SU(3)$ + Higgs theories: The Fundamental Case

**Elizabeth Dobson, Axel Maas, Bernd Riederer**

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Lattice 21  
Online



**NAWI Graz**  
Natural Sciences

**FWF**

Der Wissenschaftsfonds

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- Lattice results disagree qualitatively
- Explained by manifest gauge invariance qualitatively and by the Fröhlich-Morchio-Strocchi mechanism quantitatively

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- Should be testable on the lattice

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- **Ws**  $W_\mu^a$  
- **Higgs**  $h_i$  
- Couplings  $g, v, \lambda$  and some numbers  $f^{abc}$  and  $t_a^{ij}$
- There is a global  $U(1)$  symmetry for the Higgs only

# Spectrum: Textbook (perturbative)

Gauge-dependent

Vector

Scalar

Mass

0

'SU(3) → SU(2)'



# A problem on the lattice

[Fröhlich et al.'80,  
Banks et al.'79]

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- Physics has to be expressed in terms of manifestly gauge-invariant quantities
  - And this includes non-perturbative aspects...
  - ...even at weak coupling [Gribov'78, Singer'78, Fujikawa'82]
- Especially on the lattice: No gauge-fixing necessary

# Physical states

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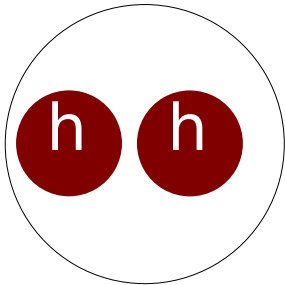
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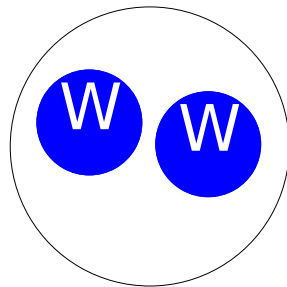
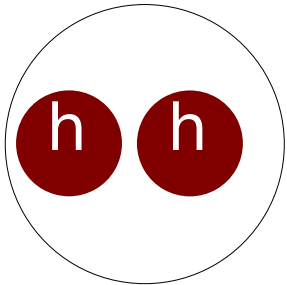
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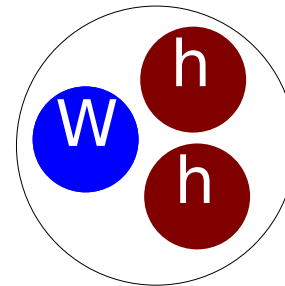
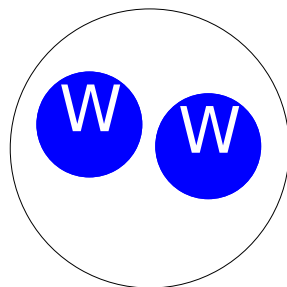
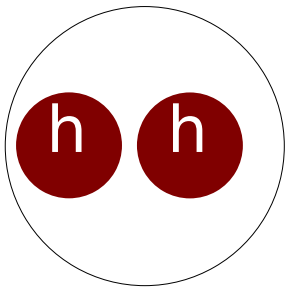
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- Need more than one particle: Composite particles
  - Higgs-Higgs, W-W



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  - **Cannot** be the elementary particles
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- Need more than one particle: Composite particles
  - Higgs-Higgs, W-W, Higgs-Higgs-W etc.



# How to make predictions

[Fröhlich et al.'80,'81,  
Maas & Törek'16,'18,  
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- $J^{PC}$  and custodial charge only quantum numbers

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  - Different from perturbation theory
    - Operators limited to asymptotic, elementary, gauge-dependent states
- Formulate gauge-invariant, composite operators
  - Bound state structure
- Depends on theory. Here:
  - Integer  $J$ , any  $P$ ,  $C$
  - Uncharged or charged under (Higgs)  $U(1)$

# Spectrum

Gauge-dependent

Vector

Scalar

Mass

0

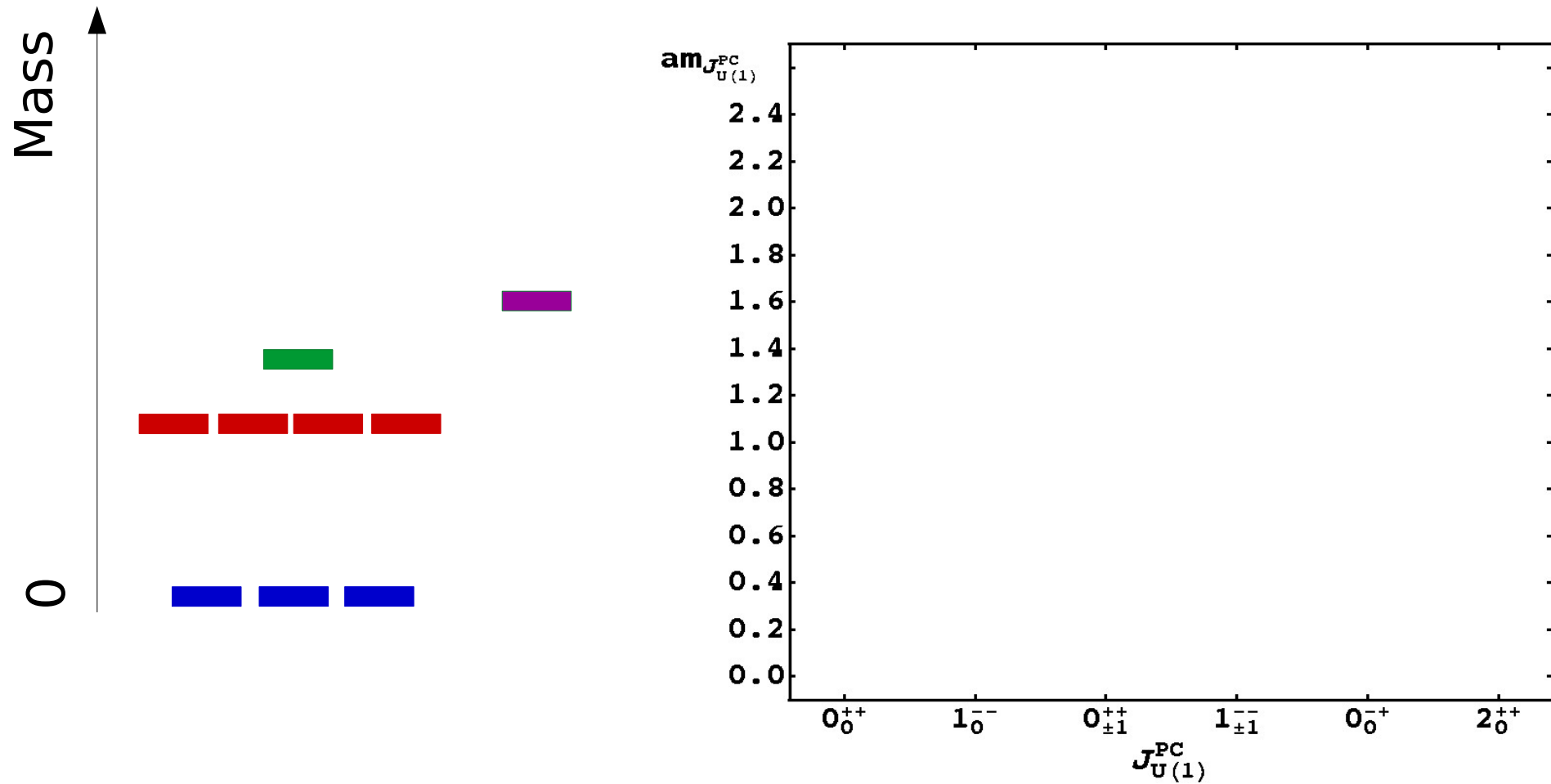


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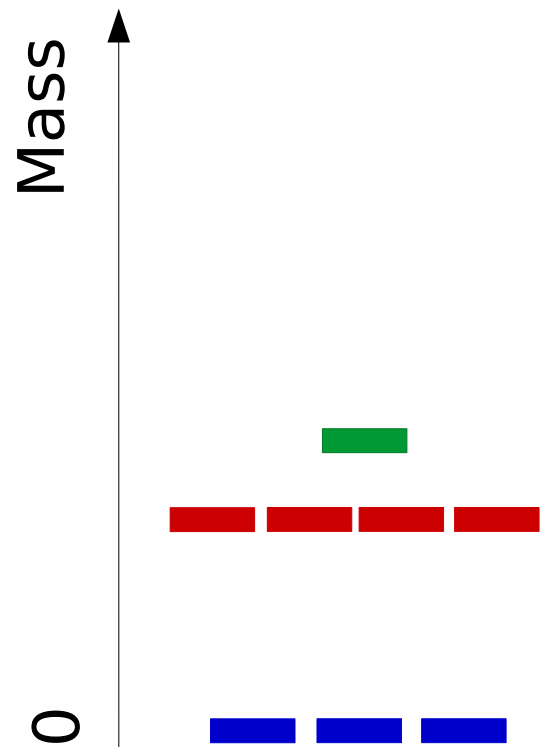
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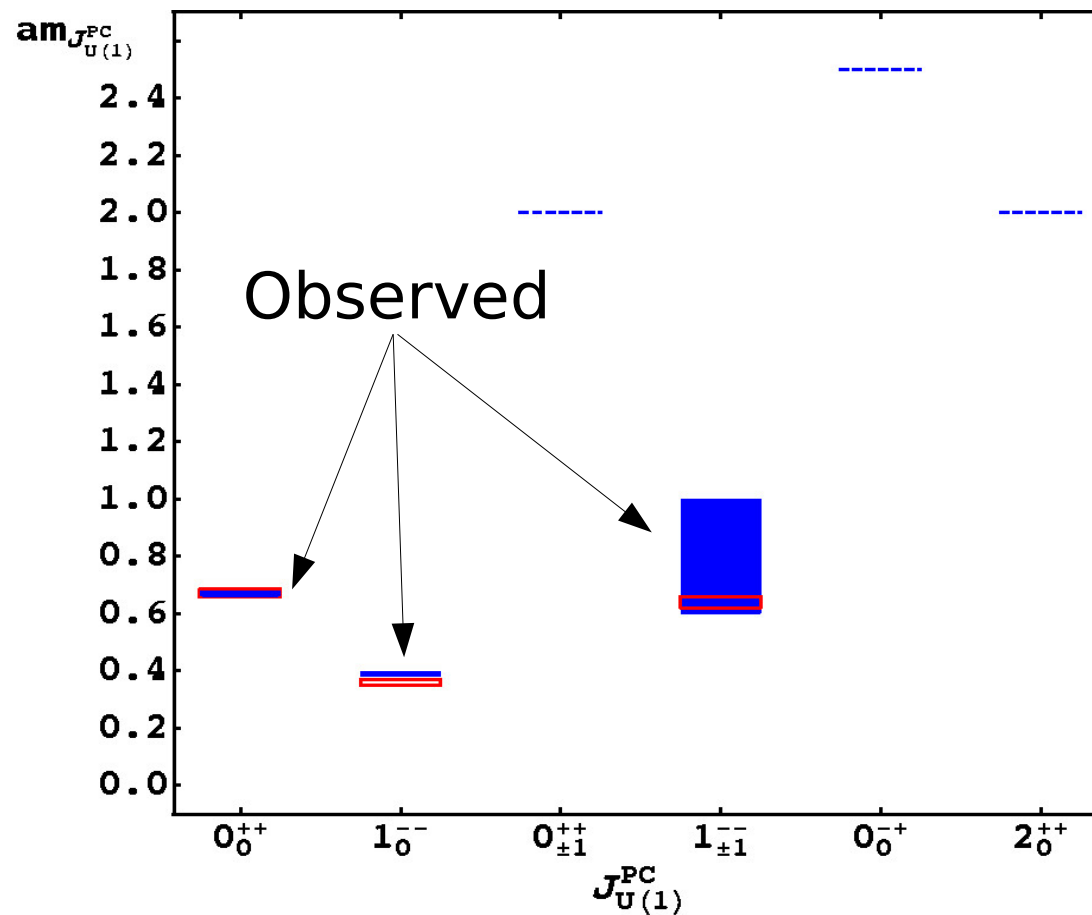
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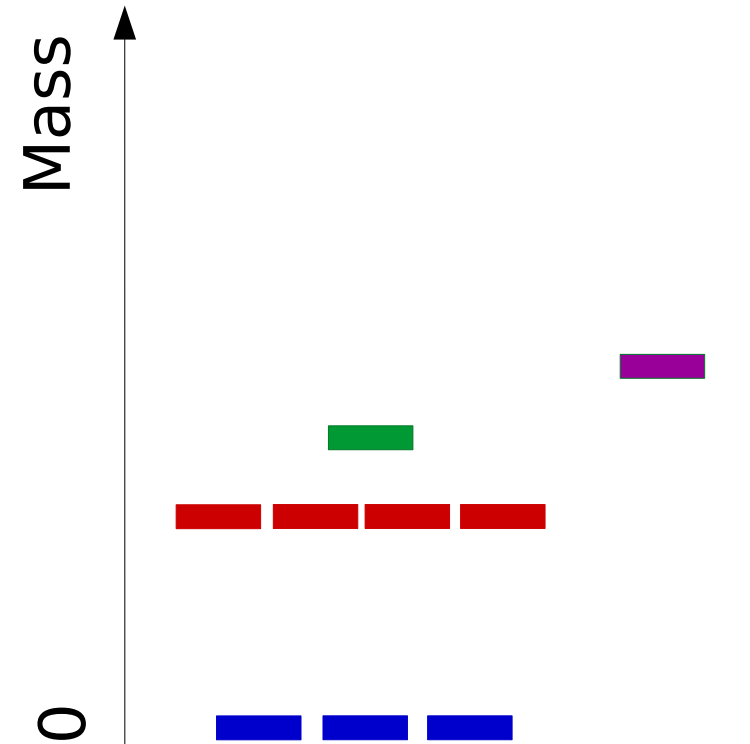
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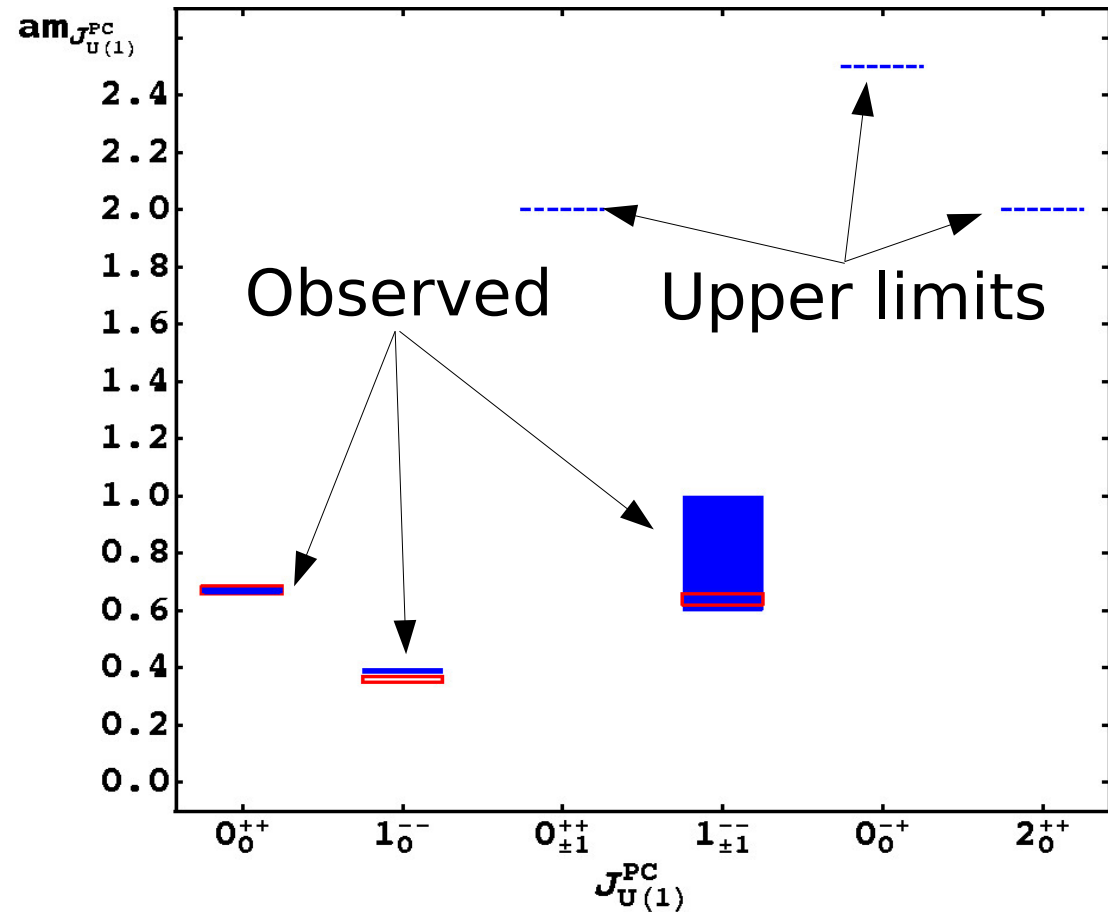
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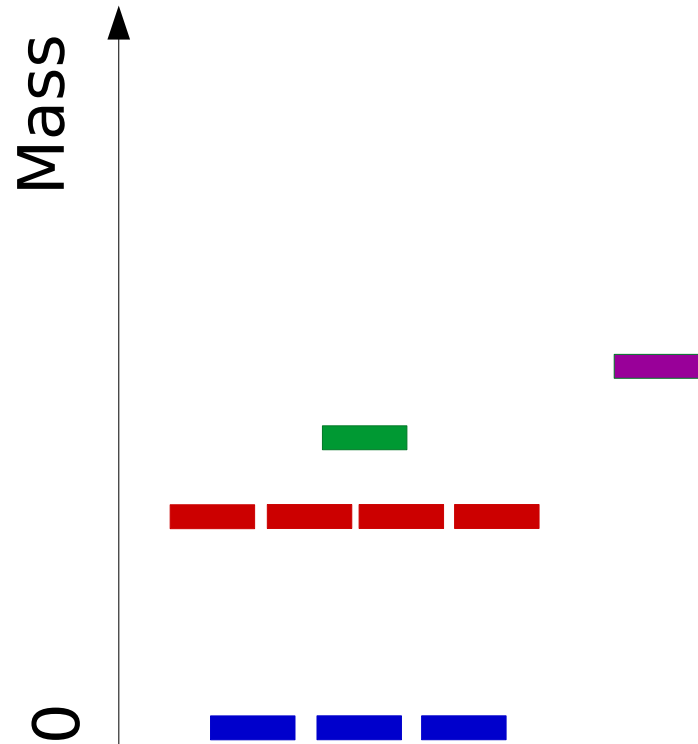


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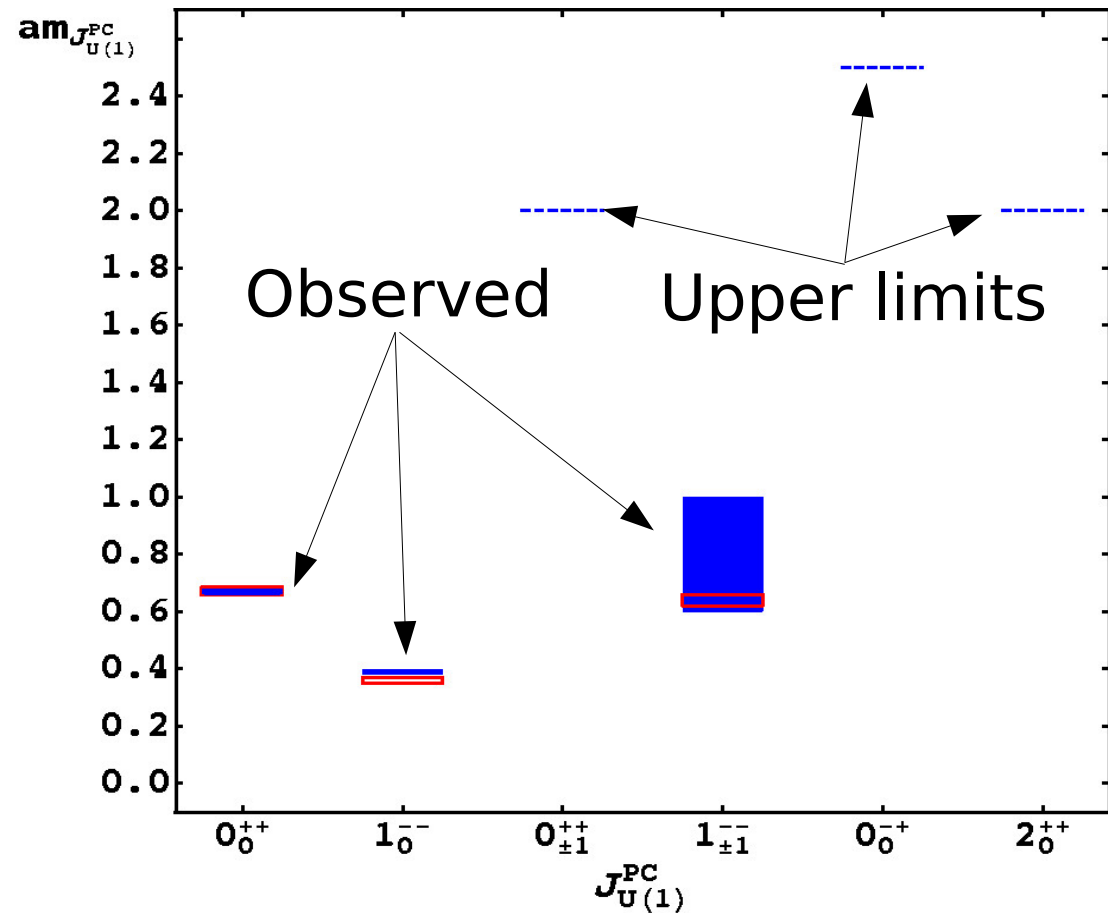
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Gauge-invariant



- Qualitatively different spectrum
- Gauge-dependent particles can also be calculated

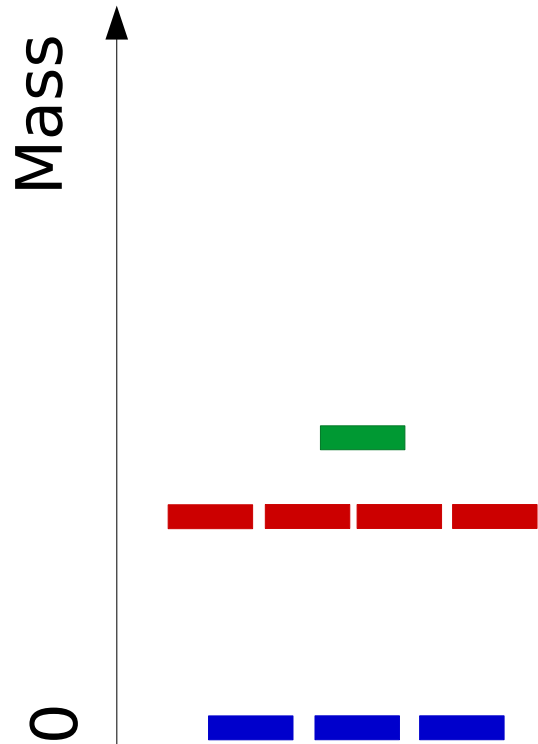
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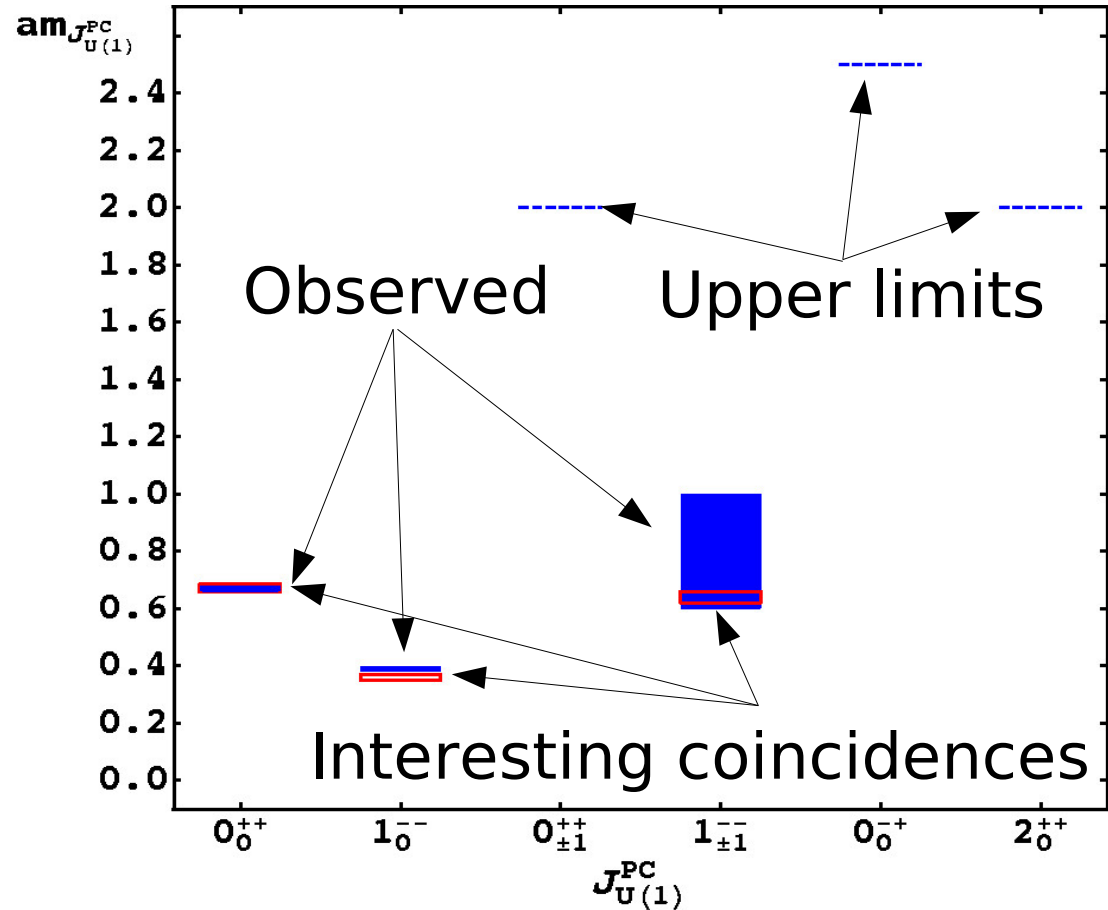
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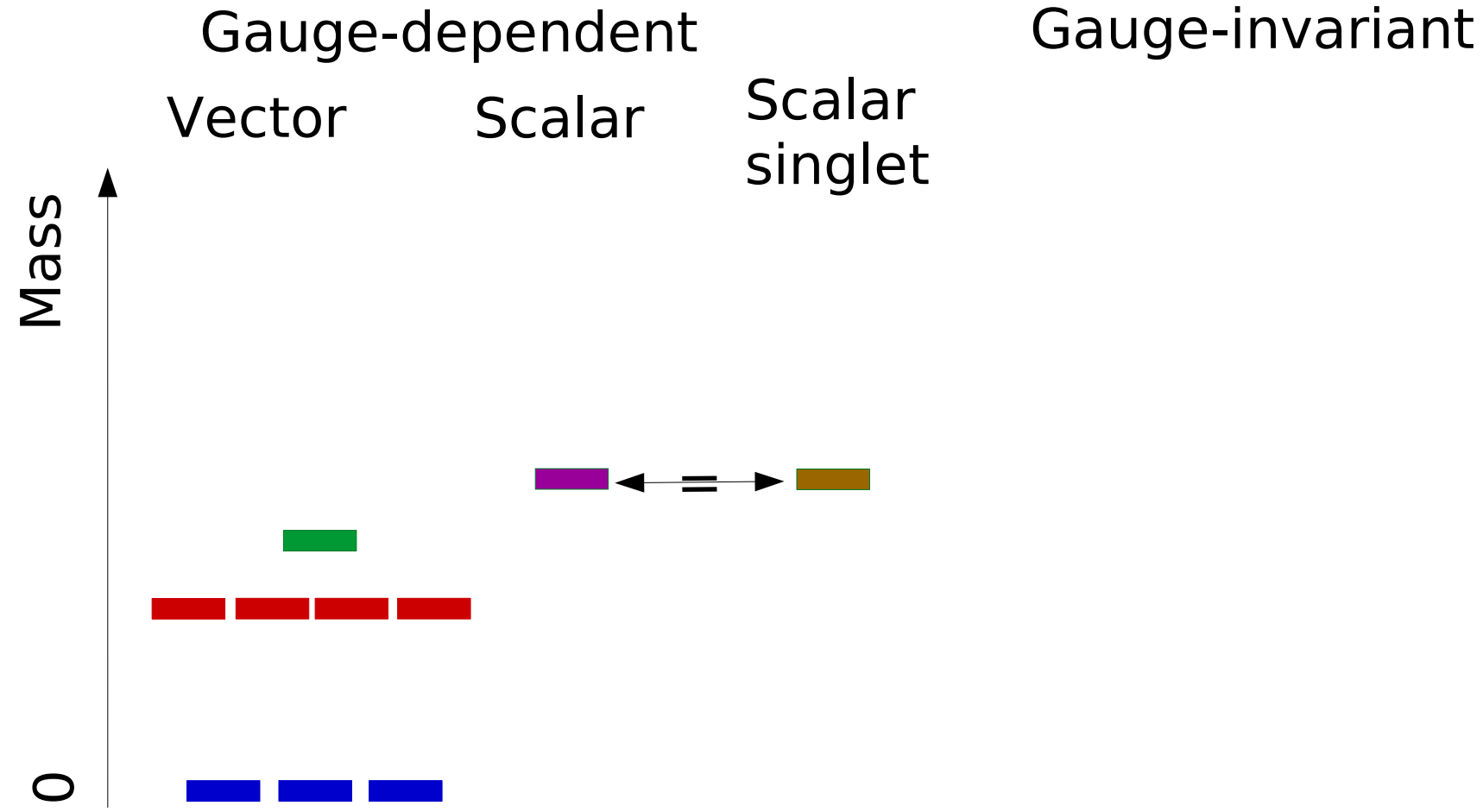
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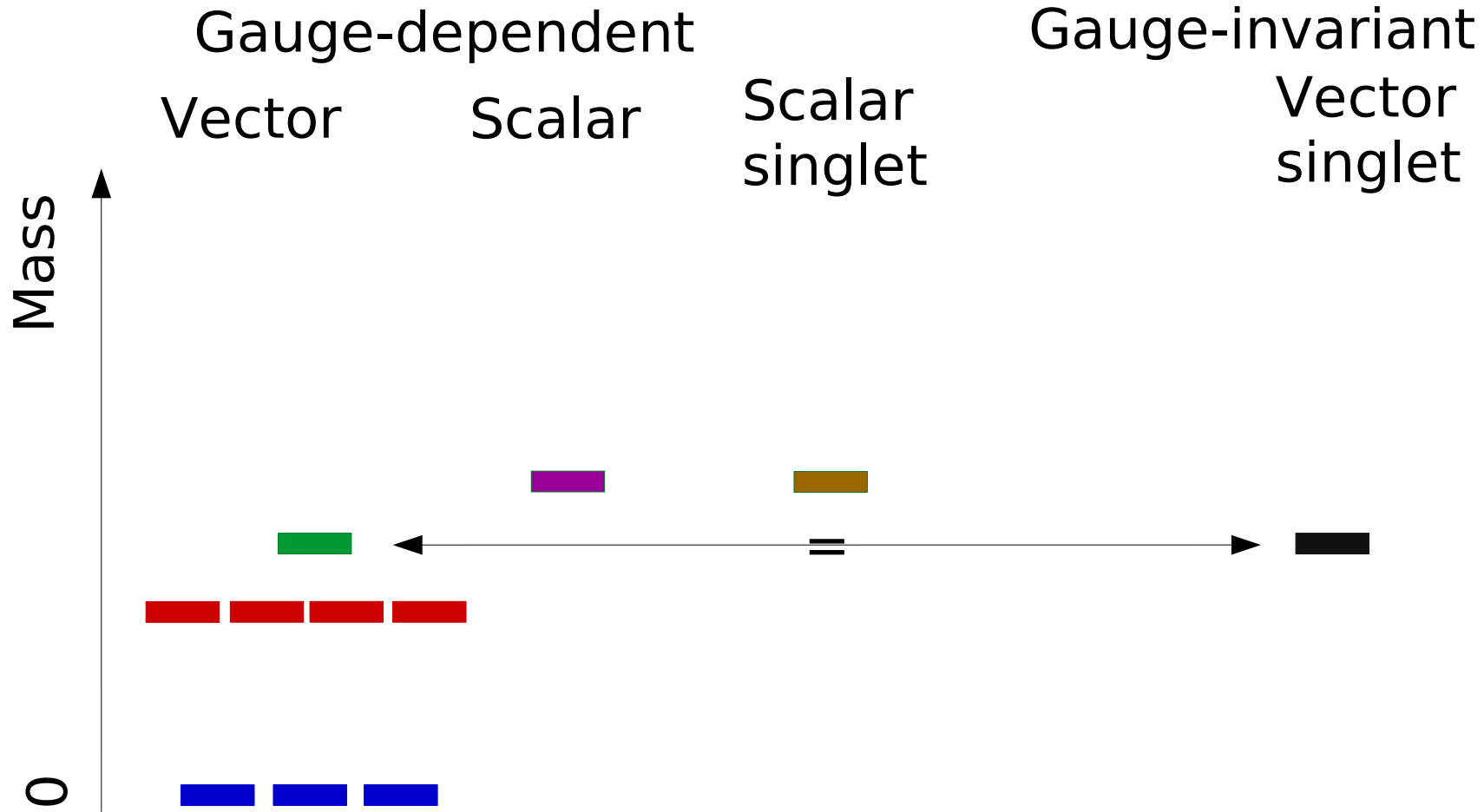
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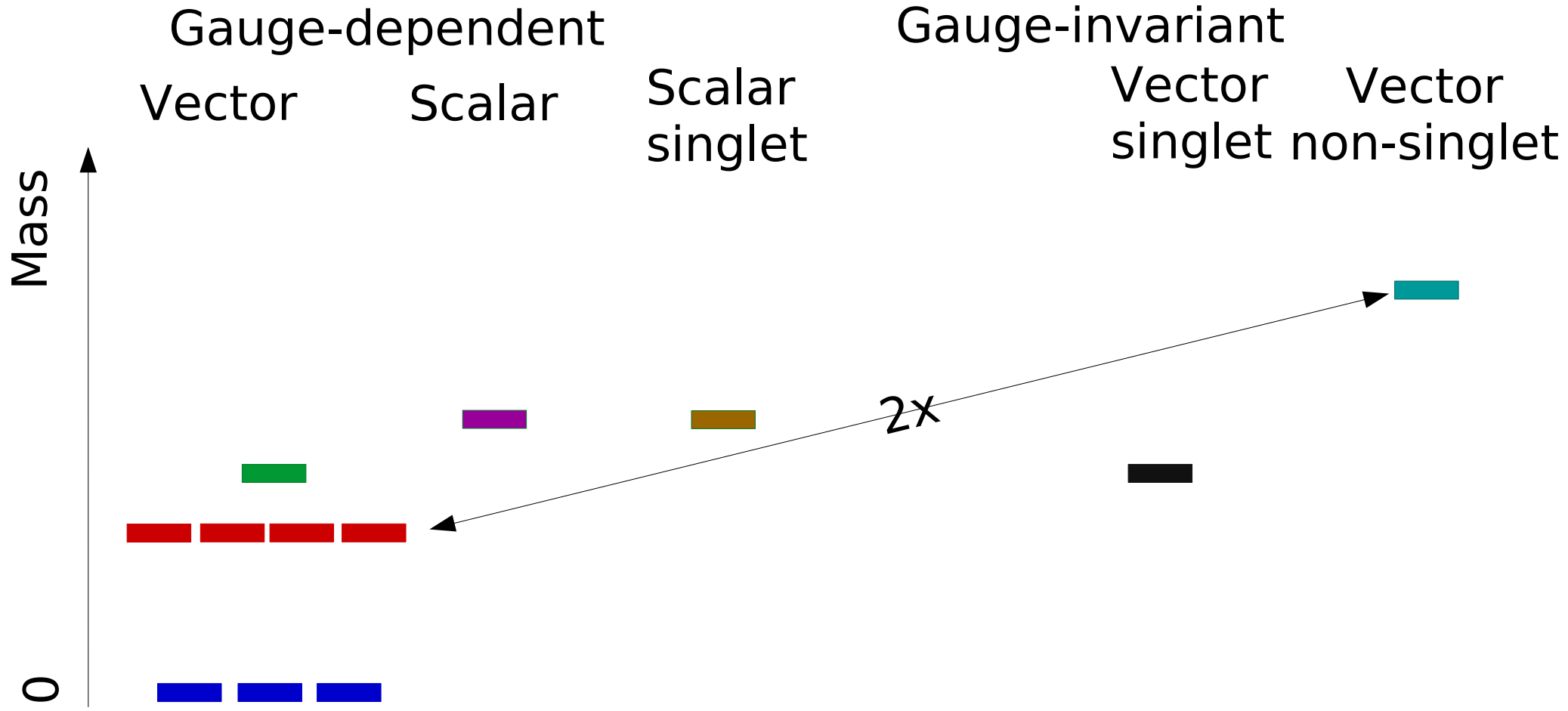
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Higgs field

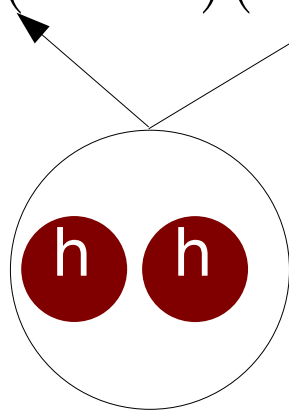


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2 x Higgs mass:  
Scattering state

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Standard  
Perturbation  
Theory

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Calculable:  $\rightarrow$  2009.06671

$$\langle (h^\dagger h)(x)(h^\dagger h)(y) \rangle = v^2 \langle \eta^\dagger(x)\eta(y) \rangle + v \langle \eta^\dagger \eta^2 + \eta^{\dagger 2} \eta \rangle + \langle \eta^{\dagger 2} \eta^2 \rangle$$

3) Standard perturbation theory

$$\langle (h^\dagger h)(x)(h^\dagger h)(y) \rangle = v^2 \langle \eta^\dagger(x)\eta(y) \rangle + \langle \eta^\dagger(x)\eta(y) \rangle \langle \eta^\dagger(x)\eta(y) \rangle + O(g, \lambda)$$

4) Compare poles on both sides

# What about the vector?

[Maas & Törek'16]

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$1^-$  singlet

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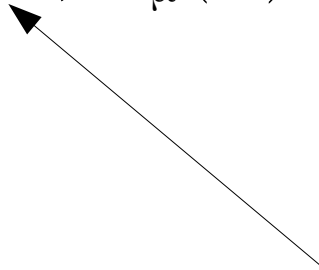
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Matrix from  
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Only one state remains in the spectrum  
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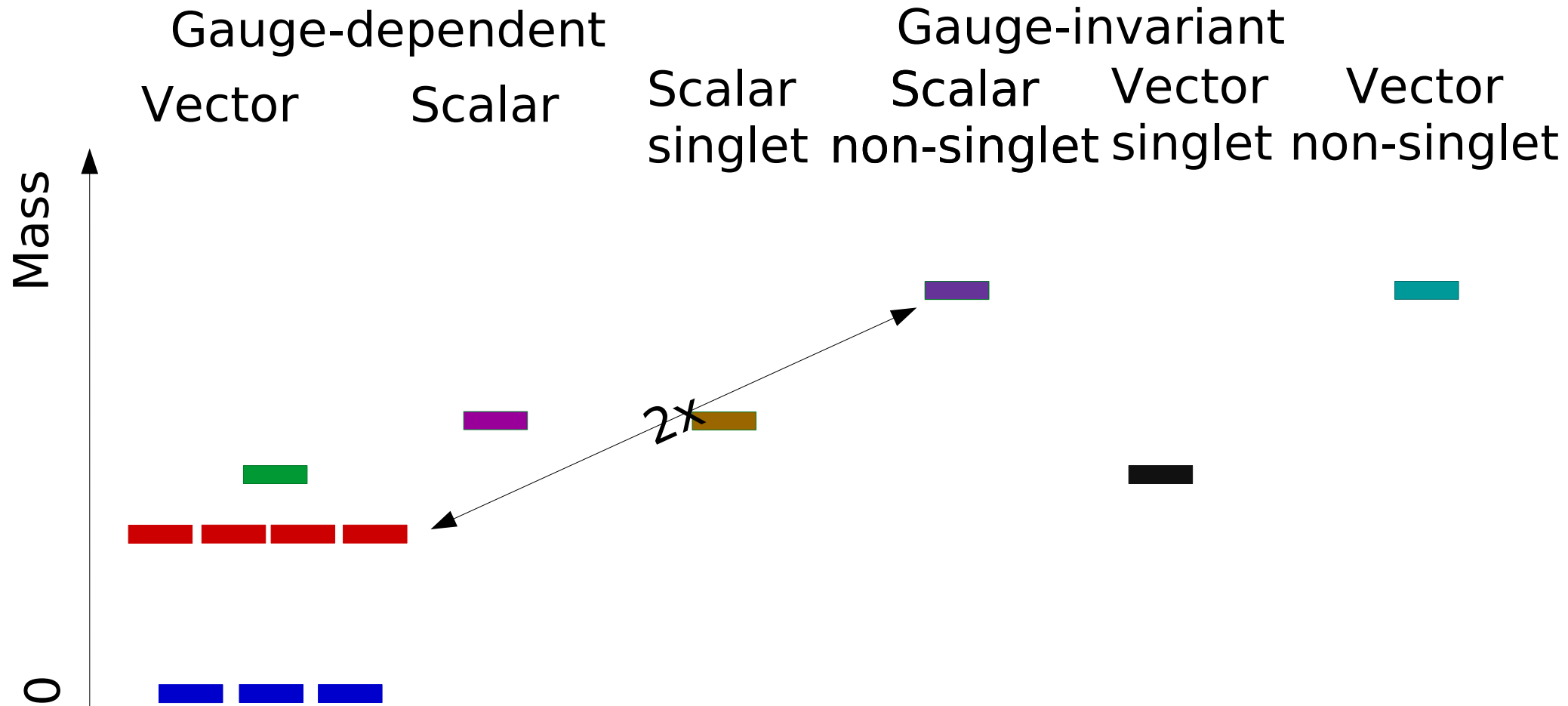
Matrix from  
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## Charged states need additional assumptions

[Maas, Sondenheimer, Törek'17]

# Spectrum

[Maas & Törek'16,'18  
Maas, Sondenheimer & Törek'17]

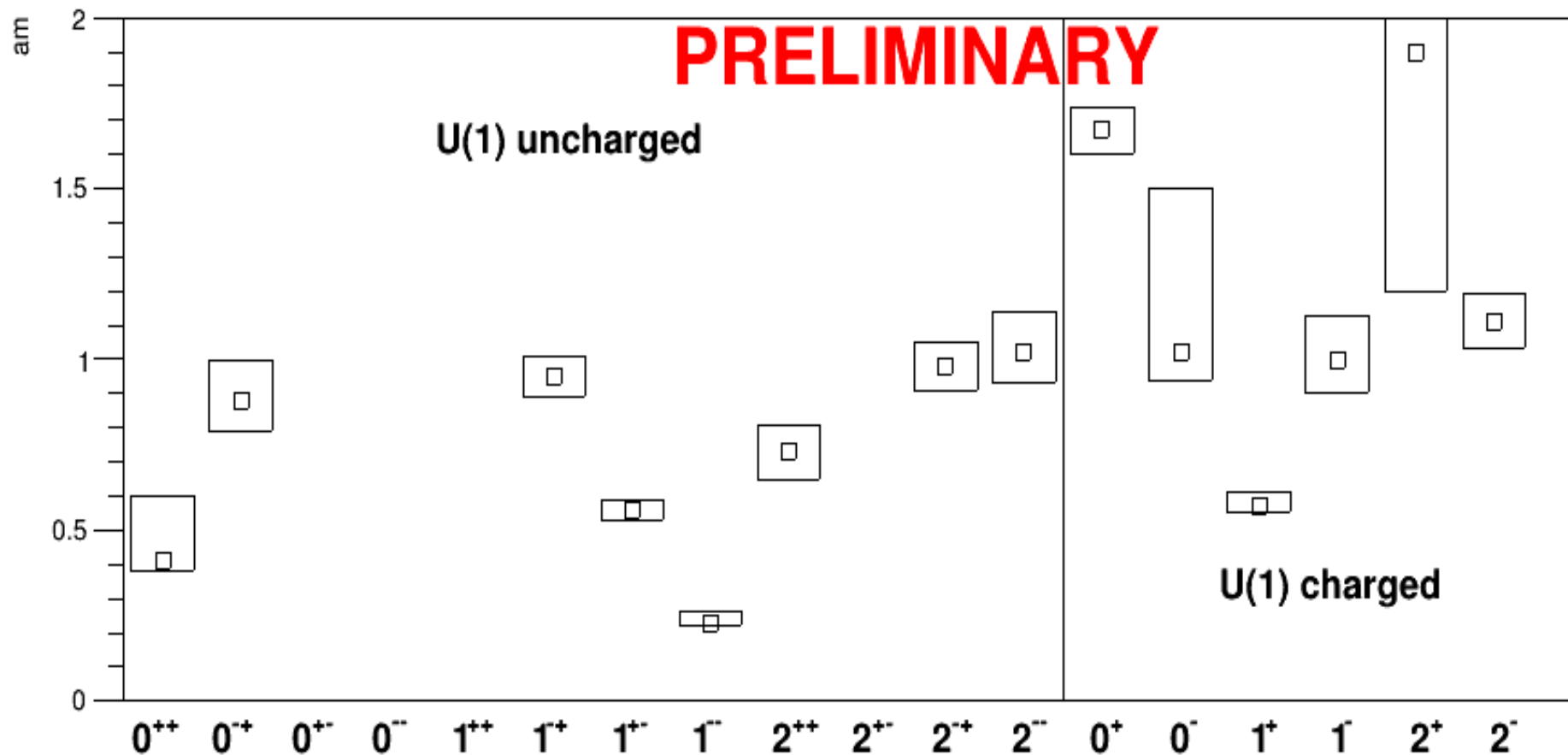


- Qualitatively different spectrum
- Gauge-dependent particles can also be calculated

# Spectrum

[Maas & Törek'16,'18  
Maas, Sondenheimer & Törek'17  
Dobson, Maas, Riedere, unpublished]

Spectrum for SU(3)+fundamental Higgs



- Full spectroscopy will check further FMS predictions
- Results so far show no additional light levels
- U(1) charged: Do not exist in perturbation theory

# Summary

- Perturbative methods to determine GUT spectra fail qualitatively
- Fröhlich-Morchio-Strocchi mechanism yields a suitable, practical alternative
- Phenomenology of GUTs needs to be redone