- voorstellen
- interrumpeer vooral
- preliminary, 'dust hasn't settled yet'
so mainly focus on ideas, rather then hardcore calculations

SUPERSYMMETRY & NONCOMMUTATIVE GEOMETRY

Thijs van den Broek
Radboud Univ. Nijmegen / NIKHEF

Workshop Bayrischzell
May 22nd, 2011

INTRODUCTION

The research project

Joint work with Walter van Suijlekom and Wim Beenakker

Try to extend the Standard Model from NCG with supersymmetry

(Everywhere: N=1 supersymmetry , i.e. MSSM)

Title may be a bit misleading

Merits come from spectral action

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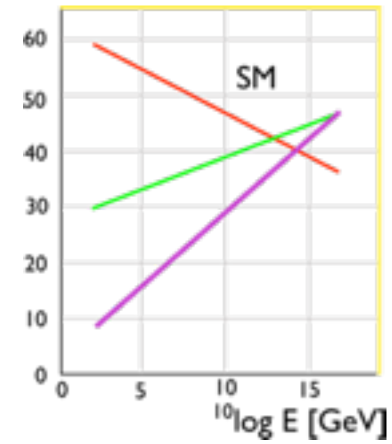
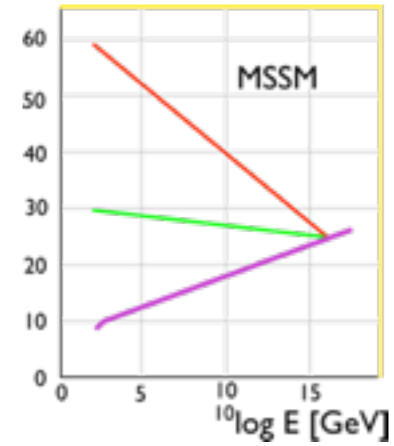
- Unification of coupling constants:



vs



Motivating example: super-QCD [1] (1/2)

Opmerken dat canoniek spectraal tripel voor de rest van het praatje geimpliceerd is.

Take:

$$(\mathcal{A},\mathcal{H},D)_{\mathrm{can}} = (C^\infty(M), L^2(M,S), c\circ\nabla^S, \gamma^5, J_M)$$

- 3, 3^o: Breakdown vanaf SM
- Dus je voegt M_3(C) toe aan de eindige Hilbert ruimte.

tensored with

$$(\mathcal{A},\mathcal{H},D)_{\mathrm{fin}} = (M_3(\mathbb{C}), \mathbf{3}\oplus M_3(\mathbb{C})\oplus \mathbf{3}^o, D_F; J_F)$$

where

$$J(q, m, \overline{q'}) = (q', m^*, \overline{q})$$

$$D_F = \begin{pmatrix} 0 & d_v & 0 \\ d_v^* & 0 & e_v^* \\ 0 & e_v & 0 \end{pmatrix} \qquad d_v(m) = mv$$

parametrizing a 3-tuple v and its conjugate.

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‘quark’ ‘gluino’ ‘antiquark’

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- Inner fluctuations

$$D_{\tilde{q}} := \sum_i a_i[D_F, b_i] \qquad a_i, b_i \in \mathcal{A}$$

parametrize (anti)squark

Extra termen = tov 'qcd'

Inner product goed?

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$$\mathcal{O}(\Lambda^0): \quad \sim f(0) R D_{\tilde{q}}^2,\ f(0)[D_\mu, D_{\tilde{q}}]^2,\ f(0) D_{\tilde{q}}^4$$

Inner product:

$$\langle \chi, D_{\tilde{q}} \psi \rangle \qquad \langle \chi_g, D_A \psi_g \rangle$$

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Inner product goed?

- SUSY automatically broken: (minus) mass terms for squarks.

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APPROACH

The approach

Problem: More realistic situations: calculations get out of hand

$\longrightarrow$ More systematical approach needed (cf. superfields)

Spectral triple is the basic object: want susy at that level

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Plan: 1) Define 'supersymmetric spectral triple'

Spectral triple is the basic object: want susy at that level

2) Prove 'susy spectral triple' $\Longrightarrow$ supersymmetric action

↗ spectral action

3) MSSM as a special case

Intermezzo: Krajewski diagrams

Waarom deze slide: dingen wat concreter maken.
Alle eigenschappen ve eindig spectraal tripel af te lezen aan K diagram

Finite spectral triple:

Krajewski diagram:

Intermezzo: Krajewski diagrams

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$\mathbf{N}_1 \quad \cdots \quad \mathbf{N}_j \quad \cdots \quad \mathbf{N}_m$

$\mathbf{N}_1^o$

$\vdots$

$\mathbf{N}_i^o$

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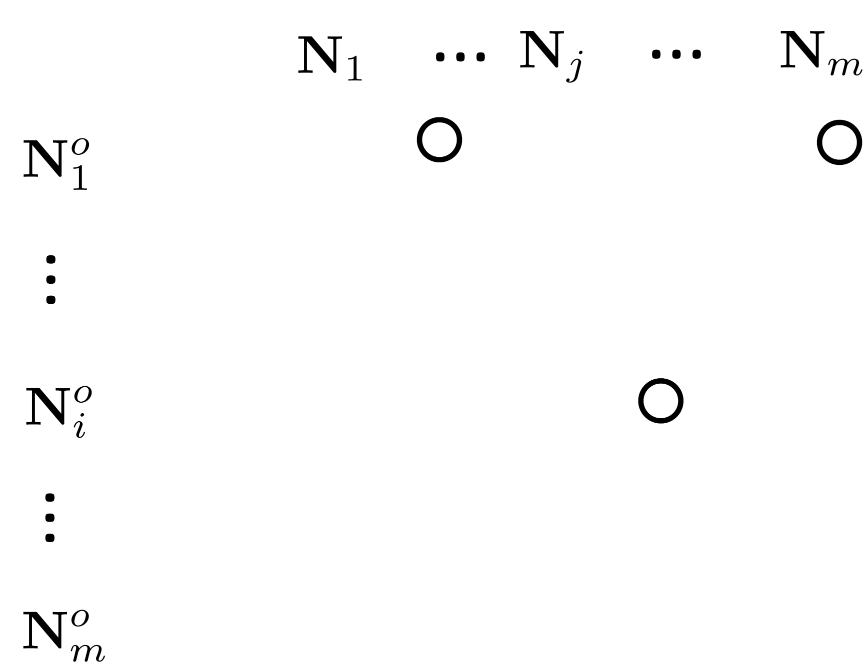

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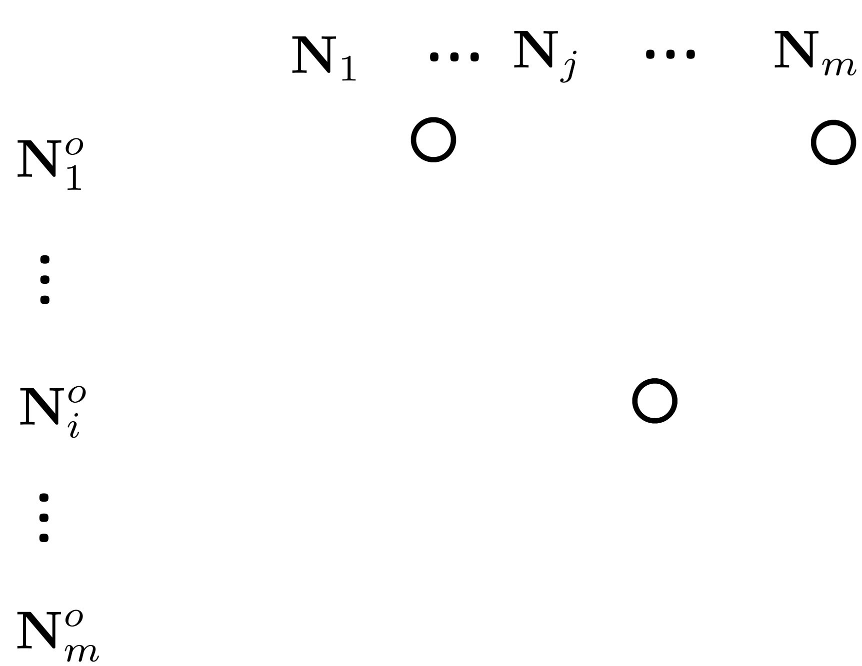

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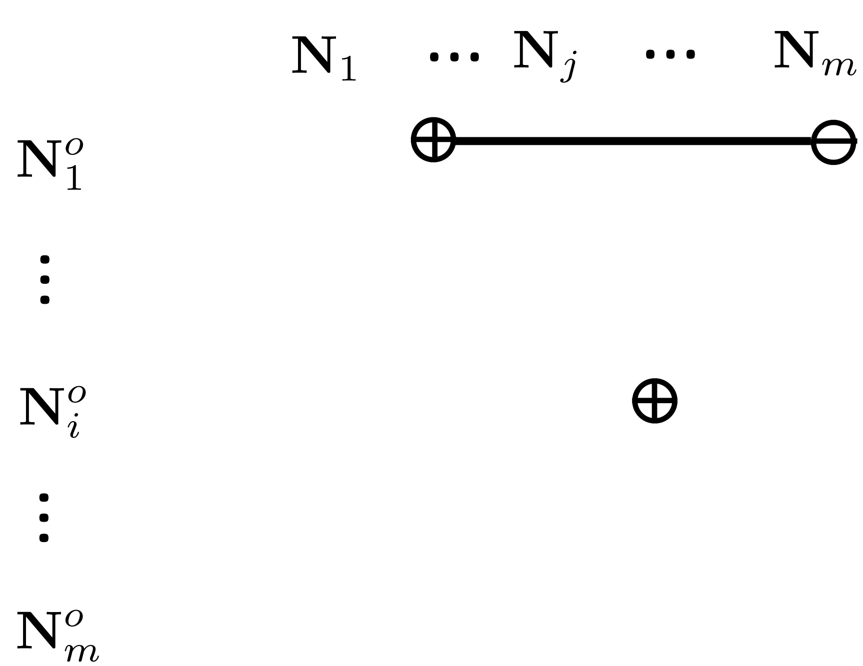

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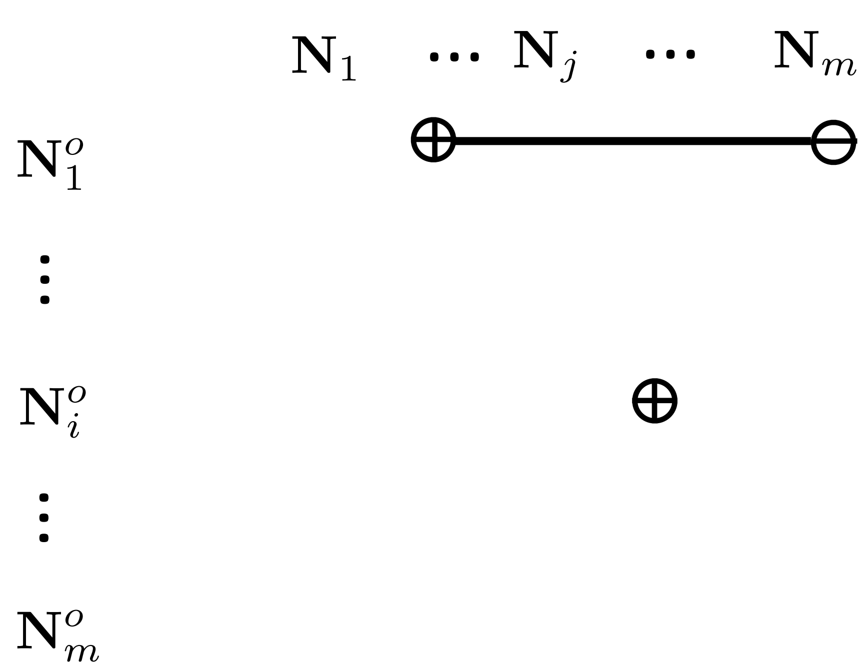

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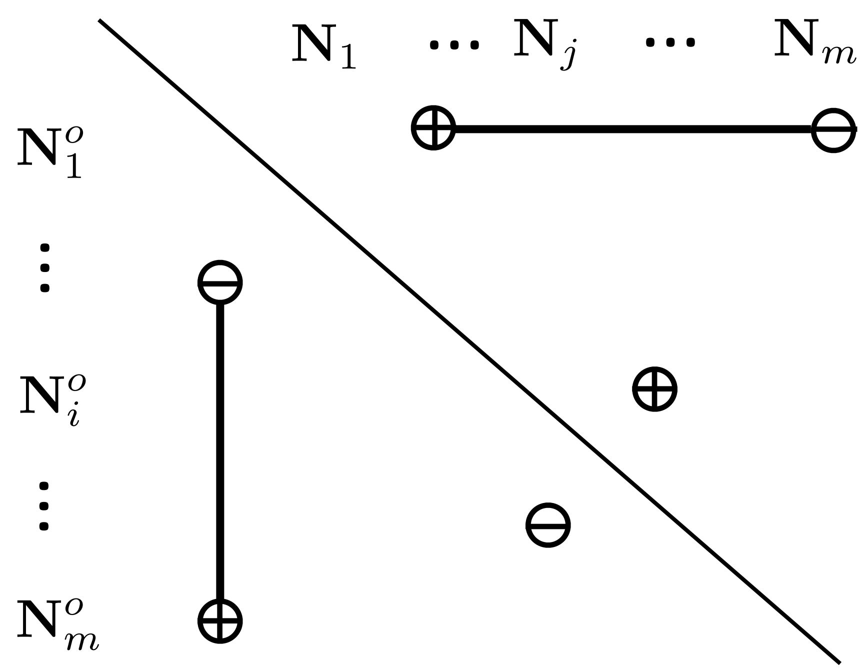

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$J^2 = \epsilon \qquad JD = \epsilon' DJ \qquad J\gamma = \epsilon'' \gamma J$

$\epsilon, \epsilon', \epsilon'' \in \{\pm\}$ ‘KO-dimension’

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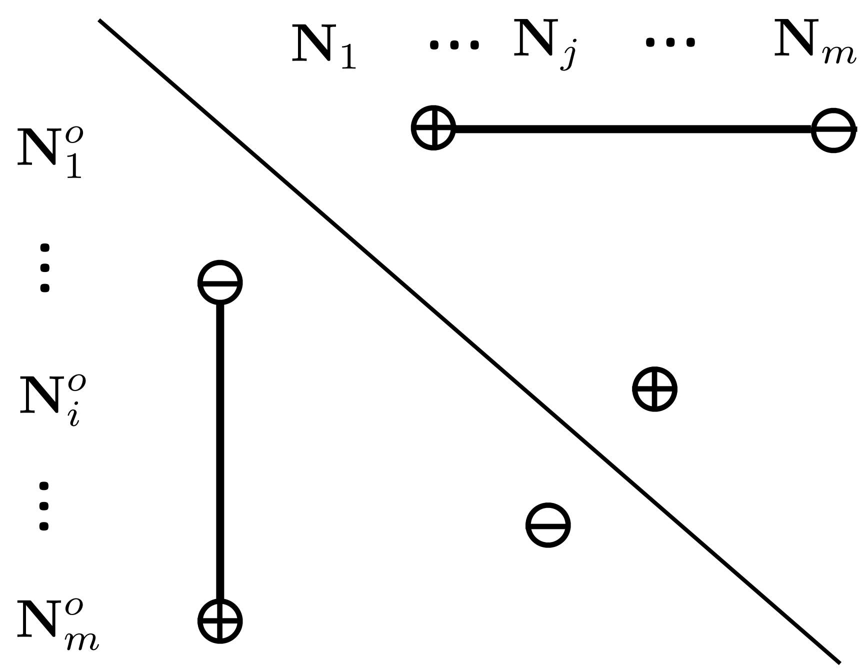

Superpartners (1/2)

General scheme as in super-QCD:

Particle	Superpartner
fermions: Hilbert space	**sfermions**: finite Dirac operator
gauge bosons: Dirac operator on M	**gauginos**: Hilbert space (adjoint reps.)
Higgs: finite Dirac operator	**Higgsinos**: Hilbert space

Superpartners (2/2)

Gauge group:

$$SU(\mathcal{A}_F) = \{u \in \mathcal{A}_F, u^* u = uu^* = 1, \det u = 1\}$$

$$U = uJuJ^*: \qquad \xi = U\xi \in \mathcal{H}_F \qquad D \to UDU^*$$

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case of super QCD fits in

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R-parity & KO-dimension (1/2)

Problem the gaugino-sector (adjoint elements of $\mathcal{H}_F$) incompatible with $J\gamma = -\gamma J$

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Solution given:

- two spectral triples $(\mathcal{A}, \mathcal{H}_{1,2}, D_{1,2}; J_{1,2}, \gamma_{1,2})$ of KO-dimension n_1, n_2 (say)
- an operator R with: $R|_{\mathcal{H}_1} = 1 \quad R|_{\mathcal{H}_2} = 1$

Direct sum: $(\mathcal{A}, \mathcal{H}_1 \oplus \mathcal{H}_2, D_1 + D_2 + D_{\text{off}}; J, \gamma)$

$$J = J_1 \oplus J_2 \qquad \gamma = \gamma_1 \oplus \gamma_2 \qquad D_{\text{off}} : \mathcal{H}_{1,2} \to \mathcal{H}_{2,1}$$

R-parity & KO-dimension (2/2)

Onderstrepen: een manier om het te zien.

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Use R to ‘even out’ the KO dimensions:

$$J^2 = R^{(1+\eta)/2}\epsilon \qquad J\gamma = R^{(1+\eta')/2}\epsilon'\gamma J \qquad JD = R^{(1+\eta'')/2}\epsilon'' DJ$$

$\Rightarrow$ three new signs η, η', η'' (‘super-KO-dimension’?)

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Example KO-dimensions 6 (SM) and 0 (gauginos) has:

$$J^2 = 1 \qquad J\gamma = -R\gamma J \qquad JD = DJ$$

i.e. $(\epsilon, \epsilon', \epsilon'', \eta, \eta', \eta'') = (+, -, +, -, +, -)$

Role 'R-parity', where $\mathcal{H}_{R=1} = \mathcal{H}_{\text{SM}} \quad \mathcal{H}_{R=-1} = \mathcal{H}_{\text{gaugino}}$

A supersymmetric spectral triple

Definition We call an R-parity extended spectral triple:

a spectral triple $(\mathcal{A}, \mathcal{H}, D; J, \gamma)$ that is extended with a grading $R : \mathcal{H} \to \mathcal{H}$ satisfying:

$$[R, a] = 0 \quad \forall a \in \mathcal{A} \qquad [R, \gamma] = 0 \qquad [R, J] = 0$$

such that

$$D_F = D_+ + D_- \qquad \text{where} \qquad RD_+ = D_+R$$

$$RD_- = -D_-R \qquad (D_- \equiv D_{\text{off}})$$

$$\text{with only} \qquad D_+\gamma = -\gamma D_+$$

We write: $(\mathcal{A}, \mathcal{H}, D; J, \gamma, R)$

A supersymmetric spectral triple

Definition We call an R-parity extended spectral triple:

a spectral triple $(\mathcal{A}, \mathcal{H}, D; J, \gamma)$ that is extended with a grading $R : \mathcal{H} \to \mathcal{H}$ satisfying:

$$[R, a] = 0 \quad \forall a \in \mathcal{A} \qquad [R, \gamma] = 0 \qquad [R, J] = 0$$

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Hope (still) The action resulting from such a spectral triple (via the spectral action principle) is automatically supersymmetric.

APP

APPLICATION

Why the SM?

A nice way to look at things is provided by Chamseddine & Connes [2]:

- Look for irreducible solutions $\mathcal{H}_F$ of a pair $(\mathcal{A}_F^{\mathbb{C}}, J)$:

Chamseddine & Connes, Why the Standard Model, 0706.3688v1 [hep-th]

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Why the SM $\longrightarrow$ Why the MSSM

Observation:

Given the solution $\mathcal{A}_F^{\mathbb{C}} = M_N(\mathbb{C}) \oplus M_N(\mathbb{C})$ for the algebra we we can take not only $\mathcal{H}_F = M_N(\mathbb{C}) \oplus M_N(\mathbb{C})$ but in addition to that also the solution $\mathcal{H}'_F = M_N(\mathbb{C})$ for each of the two components of the algebra:

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There is an R-parity operator:

$$R = (1, -1, -1, 1)$$

(From $R = -(1, -1) \otimes (1, -1)^o \in \mathcal{A}_F \otimes \mathcal{A}_F^o$)

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(Krajewski diagrams: $R = -1$ representations have a solid fill.)

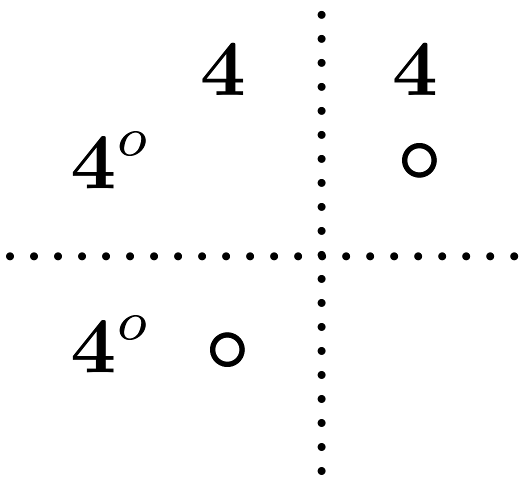
The supersymmetric spectral triple for the MSSM'

Three steps to the (MS)SM

Initial situation:

1. $\mathcal{A}_F = M_2(\mathbb{H}) \oplus M_4(\mathbb{C})$

   $\mathcal{H}_{\text{full}} = M_4(\mathbb{C})^{\oplus 4}$



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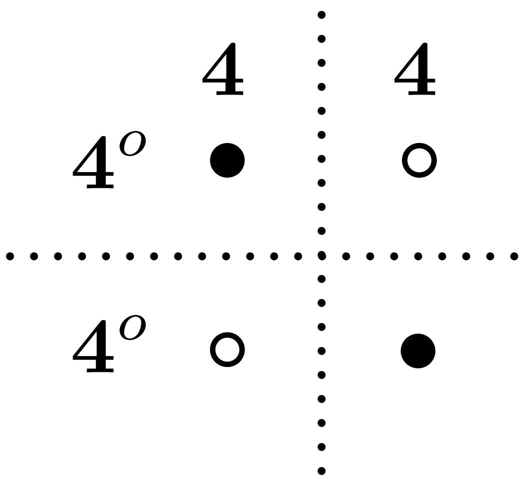

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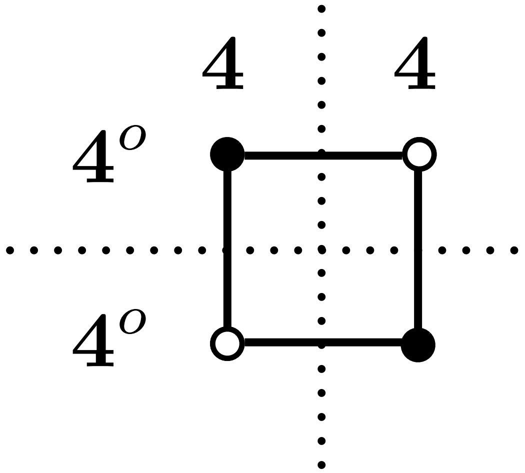

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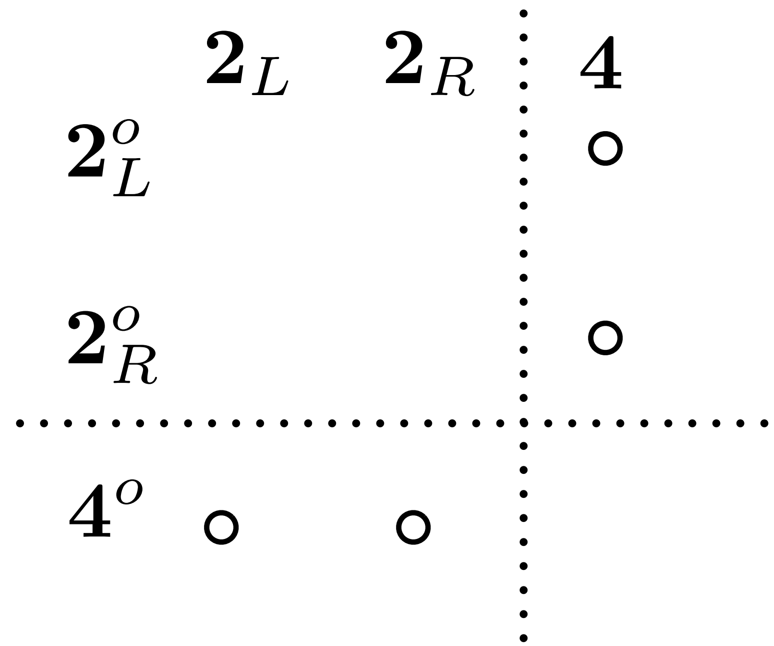

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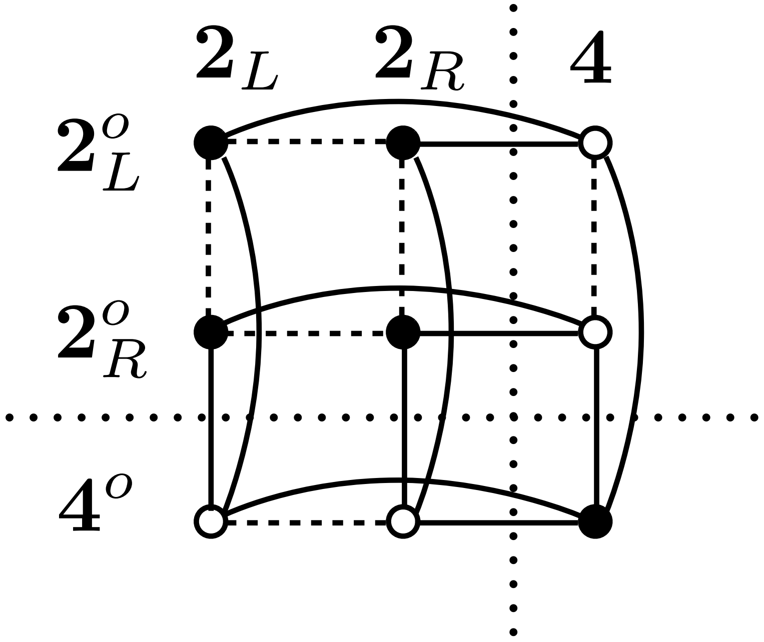

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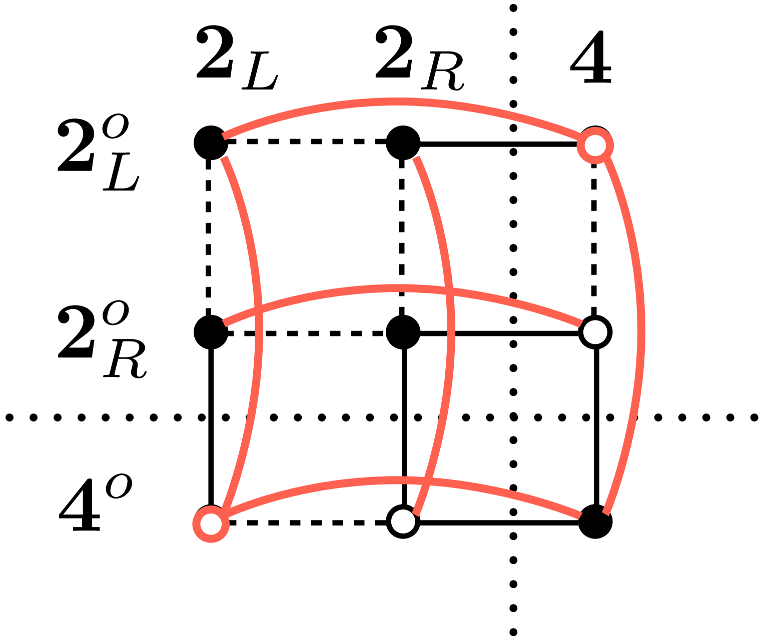

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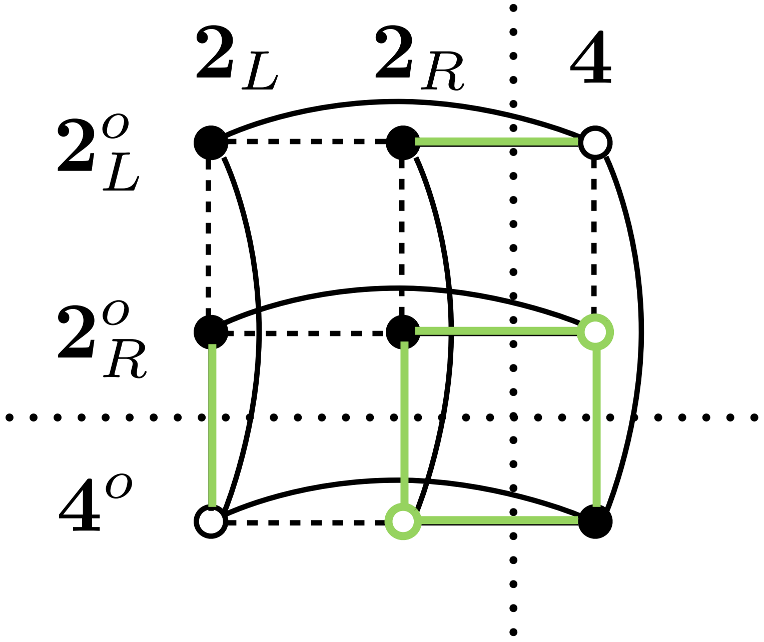

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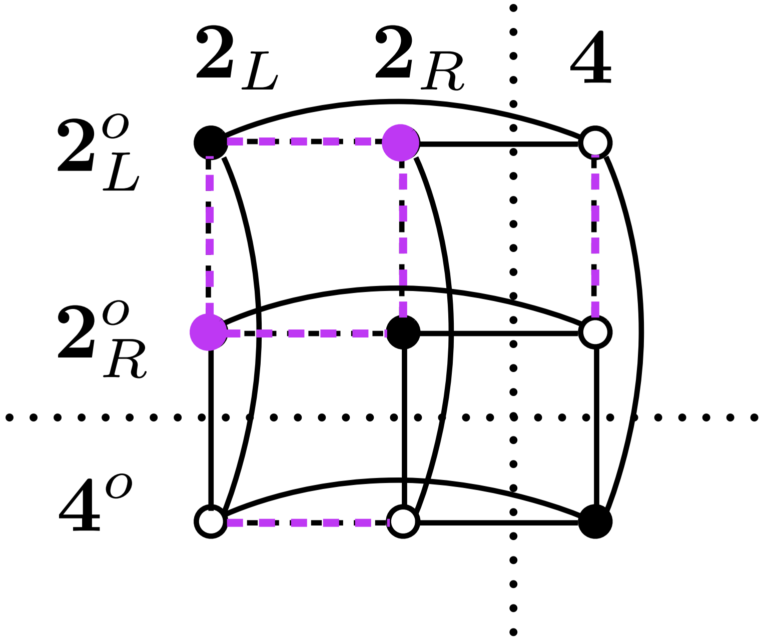

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↓

3. $\mathcal{A}_F \sim \mathbb{C} \oplus \mathbb{H} \oplus M_3(\mathbb{C})$

By adding a Majorana mass for the right handed neutrino

	$\mathbf{2}_L$	$\mathbf{1}_R$	$\overline{\mathbf{1}_R}$	$\mathbf{1}$	$\mathbf{3}$
$\mathbf{2}_L^o$				○	○
$\mathbf{1}_R^o$				○	○
$\overline{\mathbf{1}_R}^o$				○	○
$\mathbf{3}^o$	○	○	○		
$\mathbf{1}^o$	○	○	○		

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$\mathbf{3}^o$	○	○	○	●	●
$\mathbf{1}^o$	○	○	○	●	●

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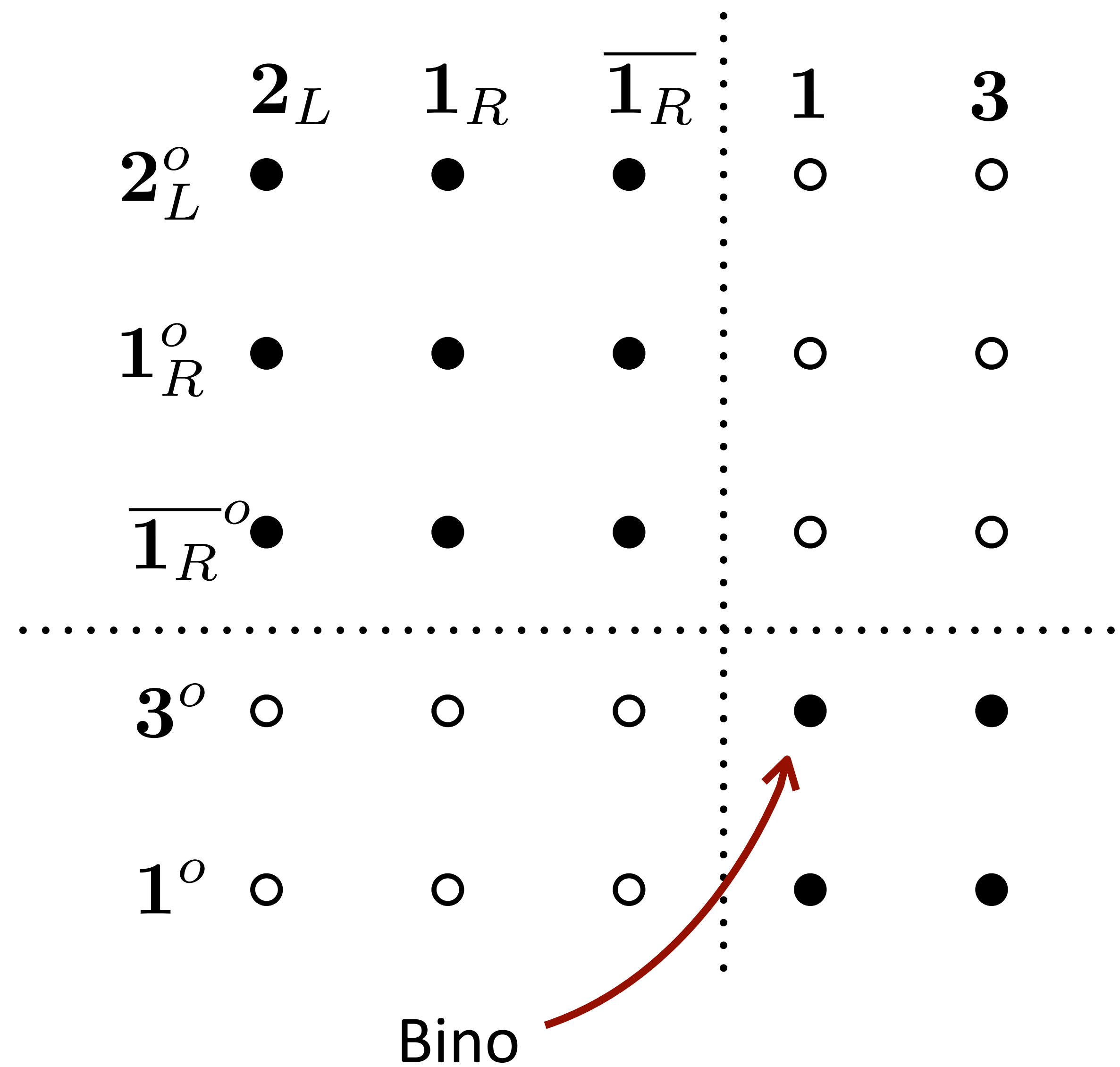

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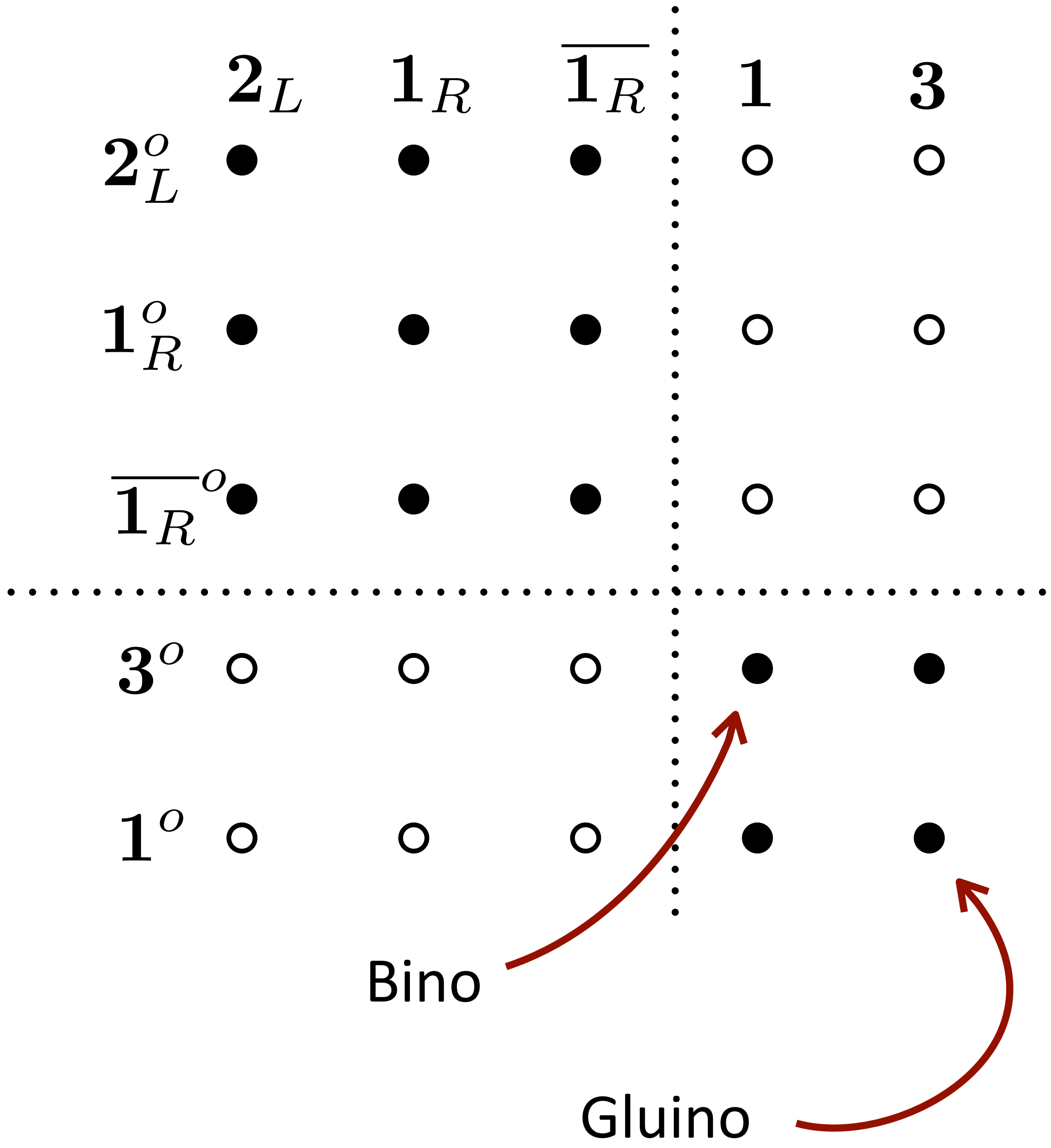

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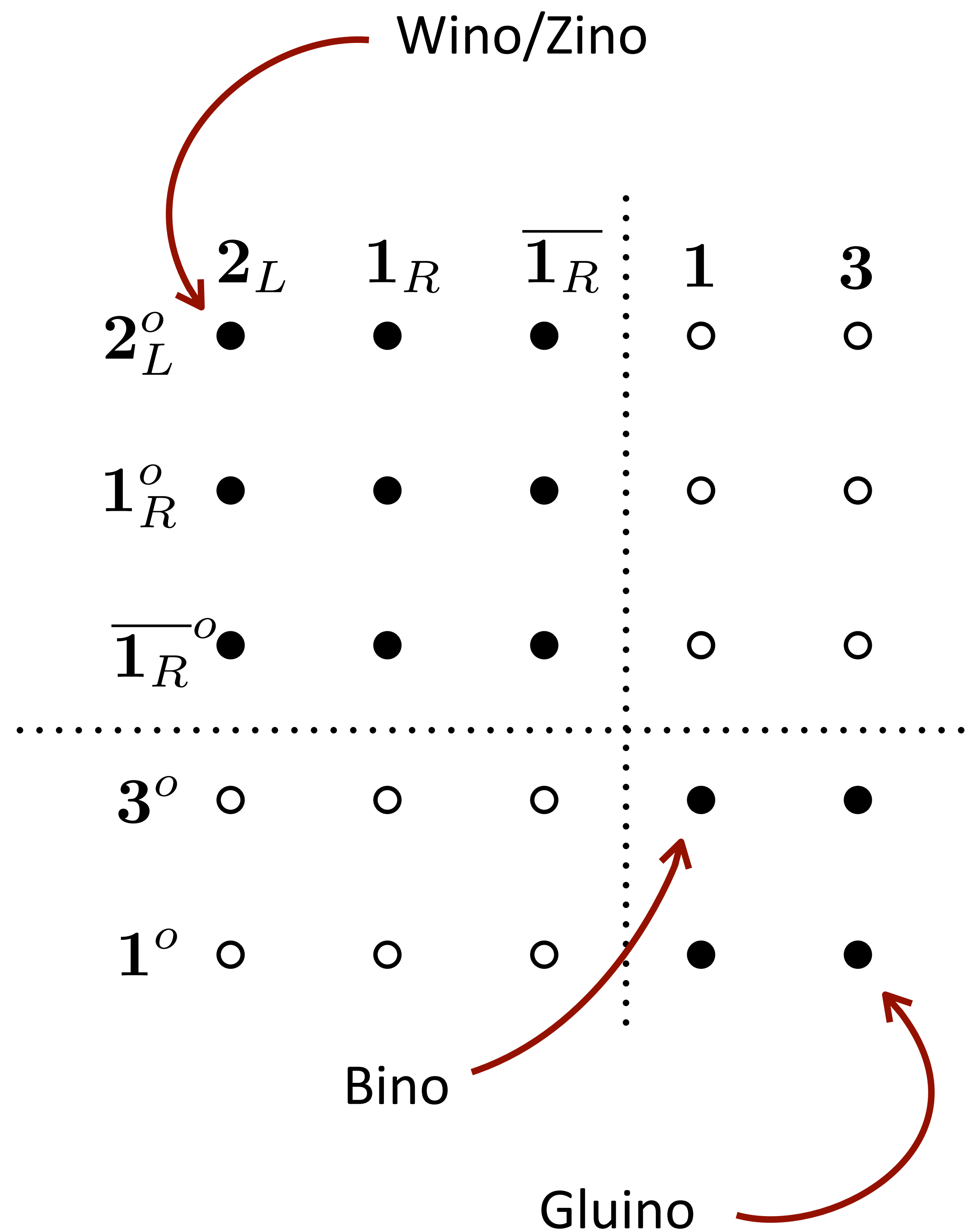

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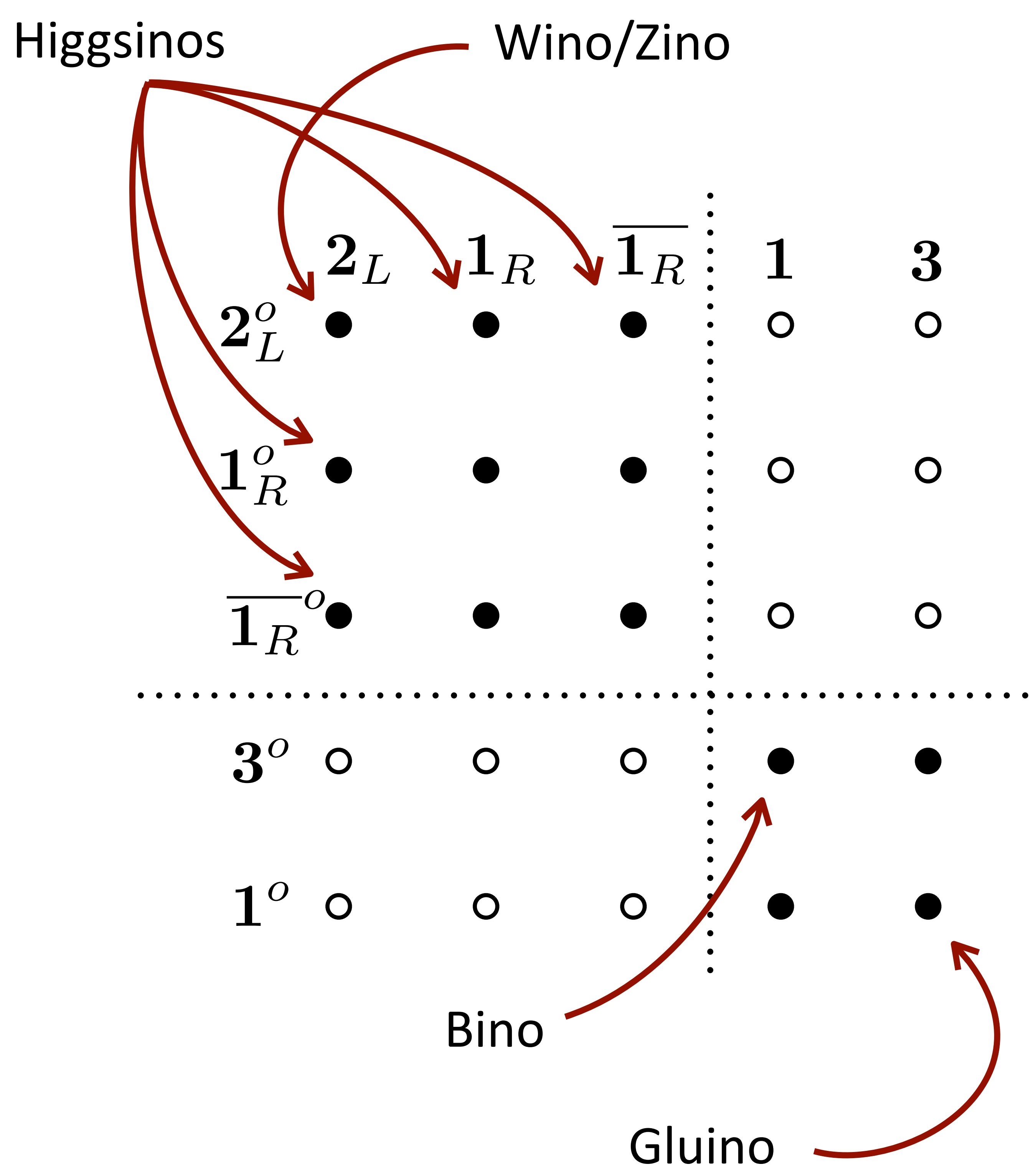

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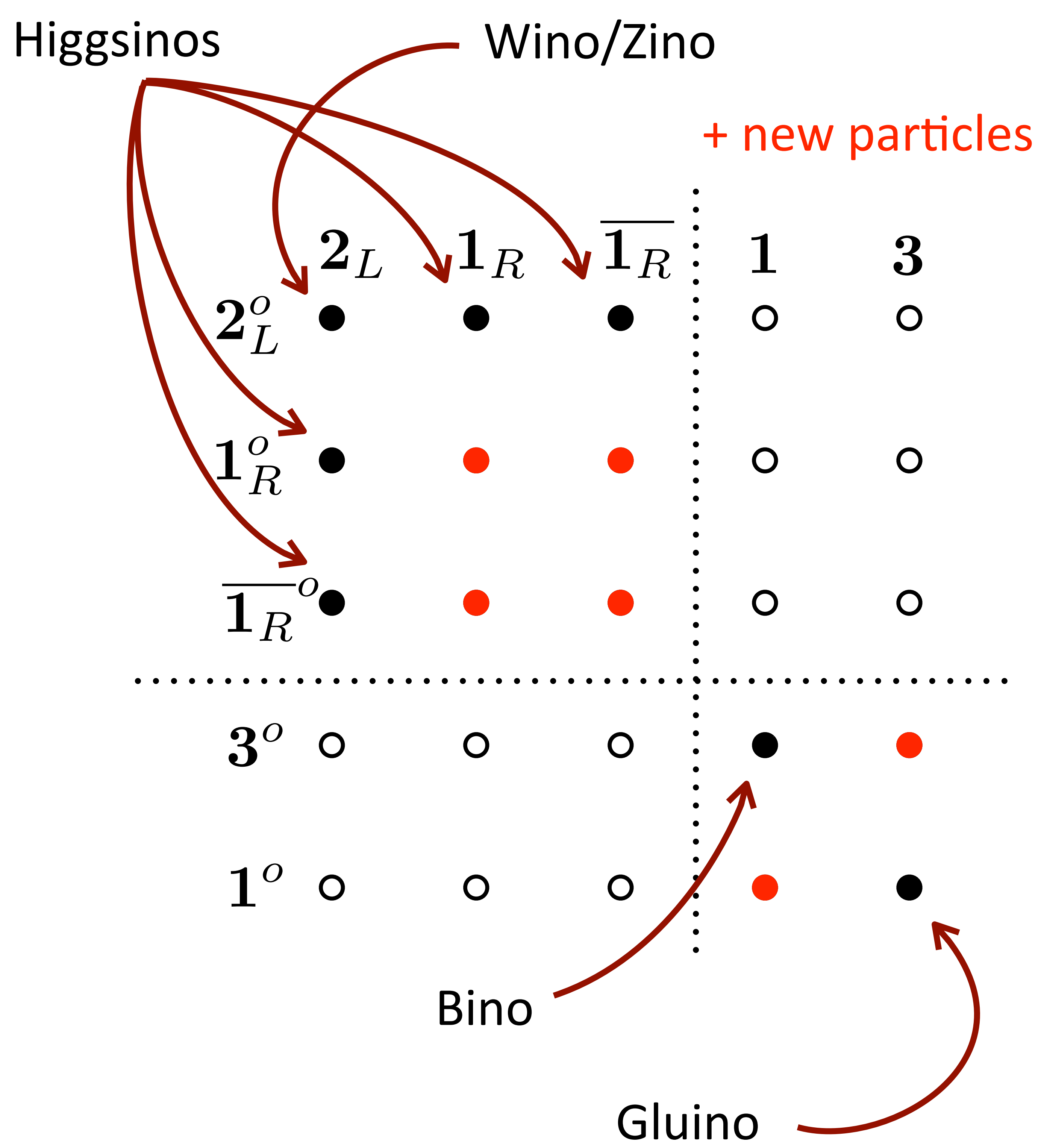

Prel

PRELIMINARY RESULTS

Gauge group | Unification

- The gauge group:

$$SU(\mathcal{A}_F) := \{u \in U(\mathcal{A}_F), \det \pi(u) = 1\} \qquad \pi : \mathcal{A}_F \to \mathrm{End}(\mathcal{H}_{\mathrm{full}})$$

is still $SU(\mathcal{A}_F) \sim U(1) \times SU(2) \times SU(3)$

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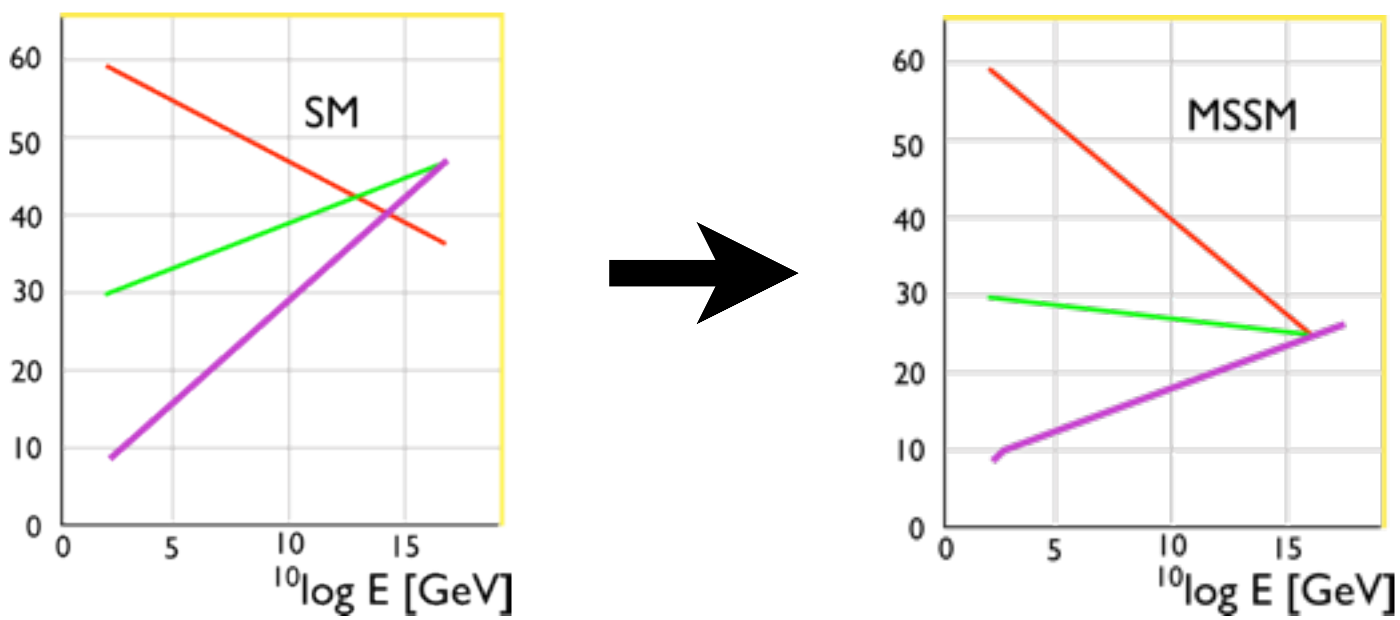
- We still have coupling constant unification: $g_3^2 = g_2^2 = \frac{5}{3} g_1^2$



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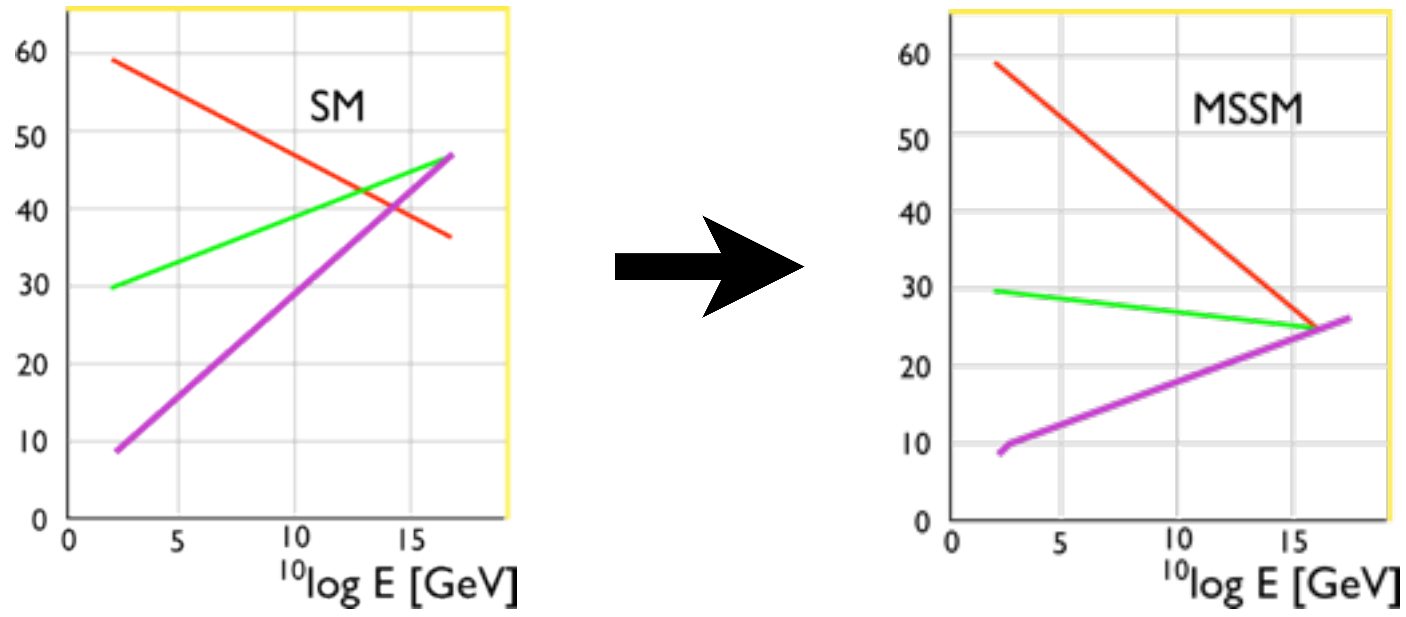

- This happens only because we have more particles than the MSSM itself provides!

Fermion doubling | Chiral anomalies

- Copies of fermions exceed those of gaugino's by a factor of four.

  Change inner product in:

$$\frac{1}{2}\langle J\zeta, (D_A + \gamma^5 \otimes D_F)\zeta\rangle \qquad \zeta \in \mathcal{H}^+ := \left[\frac{1}{2}(1+\gamma)\right]^{(1+R)/2}\mathcal{H}$$

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- Hypercharges:

	$\mathbf{1}$	$\mathbf{3}$	$\vert\uparrow\rangle_L$	$\vert\downarrow\rangle_L$	$\vert\uparrow\rangle_R$	$\vert\downarrow\rangle_R$
$\mathbf{1}$	0	$-4/3$	-1	-1	0	2
$\mathbf{3}$	$4/3$	0	$1/3$	$1/3$	$4/3$	$-2/3$
$\vert\uparrow\rangle_L$	1	$-1/3$	0	0	1	-1
$\vert\downarrow\rangle_L$	1	$-1/3$	0	0	1	-1
$\vert\uparrow\rangle_R$	0	$-4/3$	-1	-1	0	-2
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$\lvert\downarrow\rangle_L$	1	$-1/3$	0	0	1	-1
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$\lvert\downarrow\rangle_R$	-2	$2/3$	1	1	2	0

All come in pairs of opposite charges: **chiral anomalies cancel**

Comments on supersymmetry

- NCG treats bosons & fermions differently
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Try to prove susy modulo sfermion potential terms:

1. prove susy for both solutions given by C&C:
    - $(M_N(\mathbb{C}), M_N(\mathbb{C}), D_F; J, R)$
    - $(M_N(\mathbb{C}) \oplus M_N(\mathbb{C}), M_N(\mathbb{C})^4, D_F; J, R)$

Comments on supersymmetry

- NCG treats bosons & fermions differently
- No auxiliary fields (on-shell description)
- Automatically broken by sfermion masses

Nonetheless: definitely susy-like properties

Try to prove susy modulo sfermion potential terms:

1. prove susy for both solutions given by C&C:
   - $(M_N(\mathbb{C}), M_N(\mathbb{C}), D_F; J, R)$
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2. prove that susy stays intact upon breaking

OUTLOOK

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For more (conclusive) results: **stay tuned**!