A non-SUSY SO(10) model for the physics below MGUT

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from G. Altarelli and DM, JHEP **1308** , 021 (2013)

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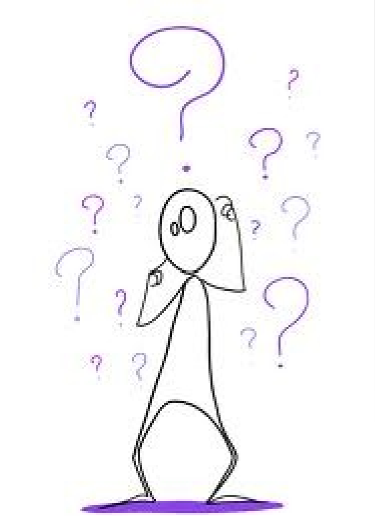
Introduction

- Absence of new-physics signals casts some doubts on the relevance of our concept of <u>naturalness</u>



"- Let us consider a theory valid up to a maximum energy... make all its parameters dimensionless by measuring them in units of Λ .

- The naturalness criterion: one such parameter is allowed to be much smaller than unity only if setting it to zero increases the symmetry of the theory

- If this does not happen, the theory is unnatural"

t'Hooft, in G. Giudice, arXiv:0801.2562

- It worked in the past

Naturalness as a good guiding principle

- Electromagnetic energy of an electron as a sphere of radius r: α/r

this must be smaller than the

total energy of the electron: m_e

r> α/m_e >> atomic radius !!

Solution of the puzzle:
New Physics sets in before the energy scale $r^{-1} \sim m_e/\alpha$.
The positron has to be included in a consistent RQFT

- Mixing in the K^0 and $\overline{K^0}$ system

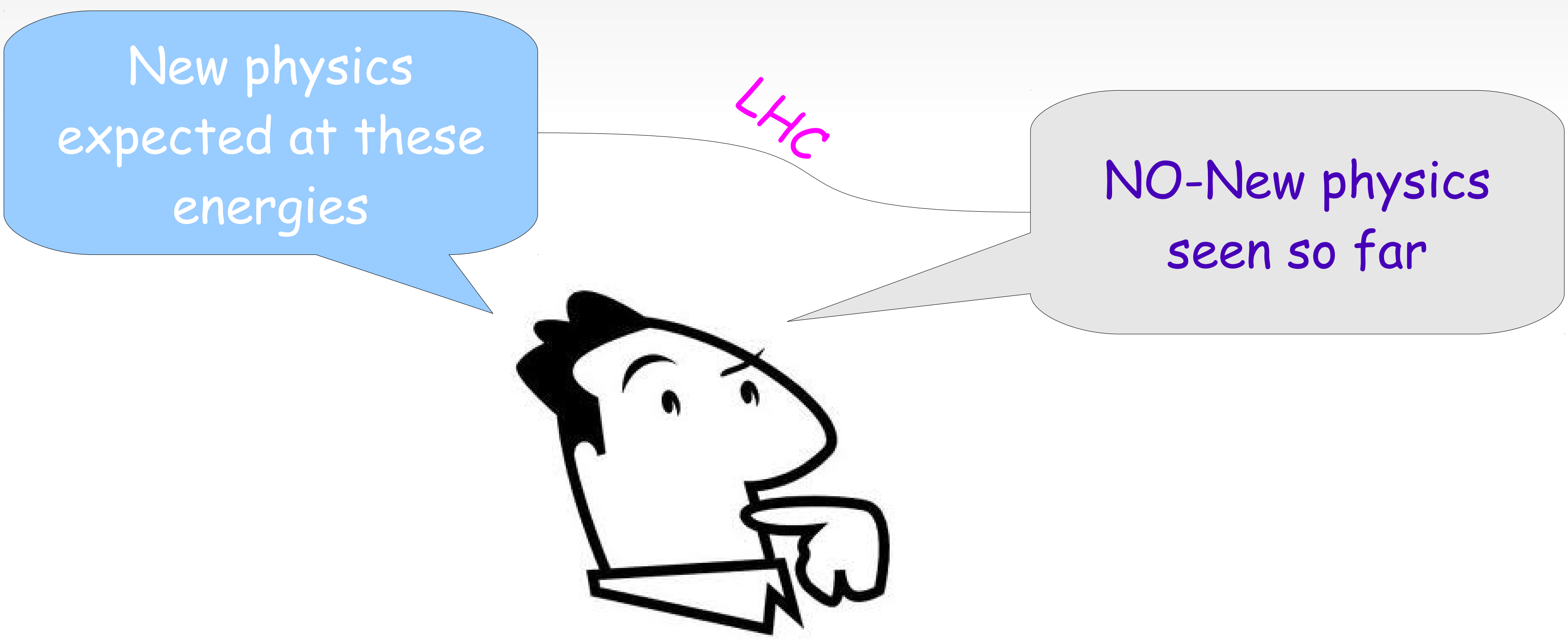
$$\frac{m_{K_L^0}-m_{K_S^0}}{m_{K_L^0}}=\frac{G_F^2 f_K^2}{6\pi^2}\sin^2\theta_C \Lambda^2=7\times 10^{-15}$$

$\Lambda <$ 2 GeV

before reaching this energy scale a new particle (the c-quark with $m_c \approx$ 1.2 GeV) modifies the short-distance behavior of the theory

For the Higgs mass...

$$\delta m_H^2 = \frac{3 G_F}{4\sqrt{2}\pi^2}\left(4 m_t^2 - 2 m_W^2 - m_Z^2 - m_H^2\right)\Lambda^2 \longrightarrow \quad \Lambda \leq O(1)\, TeV$$



Which direction?

(where precisely New Physics threshold is located?)

Building models where naturalness is restored not so far from the weak scale

Models with large fine tunings that disregard the naturalness principle in part or even completely

This scenario will be analyzed in the following

A possible BSM model

non-SUSY SO(10)

- Unification of couplings at a large scale compatible with proton decay
- A Yukawa sector compatible with all data on flavour physics, fermion masses and mixings
- Agreement with leptogenesis as the origin of the baryon asymmetry
- An axion suitable to solve the strong CP problem and account for the observed Dark Matter

The SO(10) model

- All these different phenomena can be satisfied with a single intermediate scale

$$M_I \sim 10^{11}\, GeV$$

See-saw and leptogenesis compatible with M_I

M_I also suitable for the axion to reproduce the correct Dark Matter abundance

- To be honest with you, we considered :

  - LO evolutions
  - Crude threshold matching

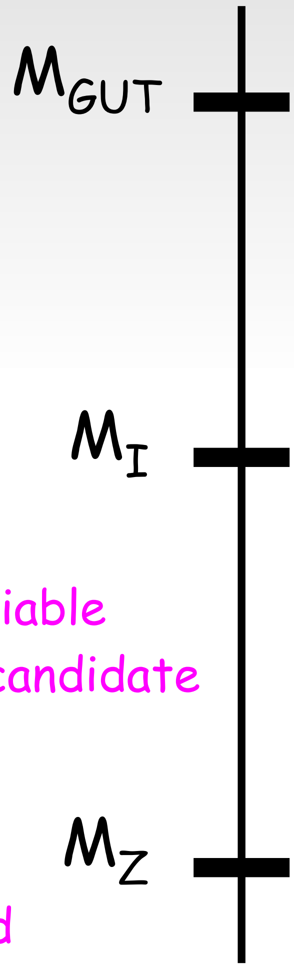
  and ignored the fine-tuning problem

Breaking chain

SO(10)

210

breaking SO(10)



$PS = SU(4) \times SU_L(2) \times SU_R(2)$

$\overline{\mathbf{126}}$ **- 45**

for breaking Pati-Salam and give fermion masses

for a viable axion candidate

$SM = SU(3) \times SU(2) \times U(1)$

10

for breaking SM and give fermion masses

Babu and Mohapatra, Phys. Rev. Lett. 70, 2845 (1993)

M_{GUT} and M_I from gauge coupling unification

- The role of the $\overline{126}$ in the coupling evolution

$$\overline{126} = (6,1,1) \oplus (\overline{10},3,1) \oplus (10,1,3) \oplus (15,2,2)$$

colored states: must be at M_{GUT}

useful for see-saw type-II; not used here

contain color singlet: used for breaking PS → SM

vev at the EW scale: involved in the evolutions SM->PS and PS->M_{GUT}

- The role of the 10 in the coupling evolution

$$10 = (6,1,1) \oplus (1,2,2)$$

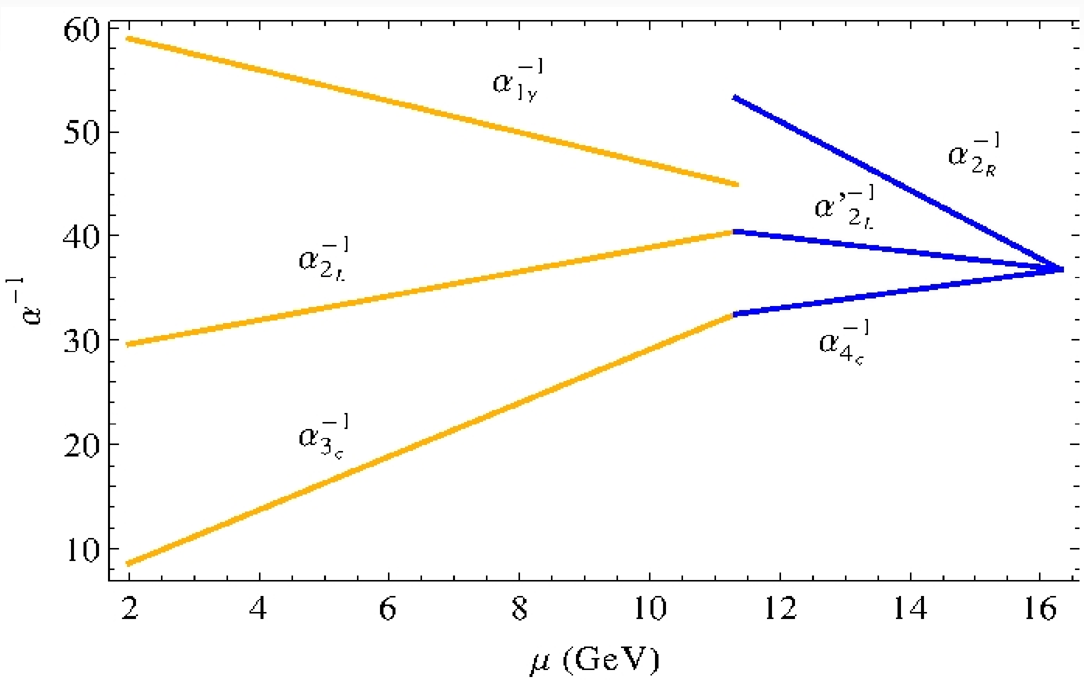
colored states: must be at M_{GUT}

vev at the EW scale: involved in the evolutions SM-> M_{GUT}

M_{GUT} and M_I from gauge coupling unification

- To 1-loop accuracy

$$\alpha_i^{-1}(M_2)=\alpha_i^{-1}(M_1)-\frac{a_i}{2\pi}\log\frac{M_2}{M_1}$$



a_3	a_{2L}	a_Y	a_4	a'_{2L}	a_{2R}
-7	-19/6	41/10	-7/3	2	28/3

$$M_I=(1.3\pm0.2)\cdot10^{11}\,GeV$$

$$M_{GUT}=(1.9\pm0.6)\cdot10^{16}\,GeV$$

$$\alpha_{GUT}\sim0.027$$

Proton decay

- naïve estimate

$$\tau \sim \frac{M_{GUT}^4}{\alpha_{GUT}^2 m_p^5} \sim 5\cdot 10^{36}\, y \gg \tau^{\exp} \equiv 10^{34}\, y$$

- from colored scalar triplet (10,1,3) with masses around M_I

Proton to K and lepton: $$\Gamma \sim g_T^2 \left(\frac{m_p^5}{M_T^4}\right) \sim \frac{m_u^2 m_d m_s \sin^2\theta_C}{v_{15}^2} \left(\frac{m_p^5}{M_T^4}\right)$$

Product of couplings of the Higgses to the fermions:

$\sqrt{m_u m_s} \sin\theta_C / v_{15}$

$\sqrt{m_u m_d} / v_{15}$

$$M_T \geq 10^{10-11}\, GeV \sim M_I$$

The Yukawa sector

- fermions in the 16 representation
- at the GUT scale, contributions from 10 and 126 Higgses

$$L_Y = 16_F \left(h\, 10 + f\, \overline{126} \right) 16_F$$

h,f complex
symmetric matrices

- The role of the 10 in the Yukawa sector

Decomposition under
SU(3)xSU(2)xU(1)

$$10 = (6,1,1) \oplus (1,2,2) \longrightarrow (1,2,2) = \left(1,2,\frac{1}{2}\right) \oplus \left(1,2,-\frac{1}{2}\right) \equiv H_u \oplus H_d$$

- if $H^*_u = H_d$ we would get m_t/m_b close to 1 → contradiction with the experimental fact
- one assumes a 10 with complex components → H_u different from H_d

$$k_{u,d} = \langle (1,2,2)_{u,d} \rangle_{10}$$

(The request for an axion candidate)

- An extra U(1) symmetry a la Peccei-Quinn is needed to avoid extra Yukawa coupling and keep the parameter space at an acceptable level:

$$16_F \to e^{i\alpha} 16_F, 10 \to e^{-2i\alpha} 10, \overline{126} \to e^{-2i\alpha} \overline{126}$$

now:

* $U(1)_{PQ}$ spontaneously broken at the EW → Goldstone boson, the axion, too strongly coupled to matter → ruled out

* $U(1)_{PQ}$ is broken by $\langle \overline{126} \rangle \neq 0$ at the scale of $SU(2)_R$ breaking

- $\langle \overline{126} \rangle \neq 0$ is not enough, since a linear combination of $U(1)_{PQ}$, T_{3R} and B-L remains unbroken

→ add another Higgs representation

The Yukawa sector

- 16 Mohapatra and Senjanovic, Z.Phys. C17, 53 (1983)
- another 126 B.Bajc et al.,Phys. Rev. D73, 055001 (2006)
- 45 → our choice to break the degeneracy
  (motivated by good gauge coupling unification)

$(1,1,3) \in 45$ with vanishing B-L and α' different from α

- The role of the $\overline{126}$ in the Yukawa sector

$$\overline{126} = (6,1,1) \oplus (\overline{10},3,1) \oplus (10,1,3) \oplus (15,2,2)$$

$$v_R = \langle (10,1,3) \rangle_{126} \neq 0 \qquad v_{u,d} = \langle (15,2,2)_{u,d} \rangle_{126}$$

Mass matrices

$$M_u = h k_u + f v_u \qquad M_d = h k_d + f v_d \qquad M_{\nu_D} = h k_u - 3 f v_u$$

$$M_l = h k_d - 3 f v_d \qquad M_\nu^M = f v_R$$ → for see-saw type-I

- Rewritten in a suitable form for a fit:

Joshipura and Patel, Phys.Rev.D83, 095002 (2011)

$$M_u = r_v \left(\frac{3+s}{4} M_d + \frac{1-s}{4} M_l \right)$$

$$M_\nu^D = r_v \left(\frac{3(1-s)}{4} M_d + \frac{1+3s}{4} M_l \right)$$

$$M_\nu^M = r_R^{-1} \left(M_d - M_l \right)$$

$$r_v = k_u / k_d$$
$$s = v_u / r_v v_d$$

M_d = down-quark mass matrix

M_l = charged lepton mass matrix

Fit procedure

- The important novelty of our approach is the introduction of the baryon-to-photon number ratio as a fit observable

$$\eta_B = (5.7 \pm 0.6) \times 10^{-10}$$

Iocco et al.,
Phys. Rept.472, 1 (2009)

- To compute η_B: implementing the Boltzmann equations

The procedure is really time-expensive

- Alternative way:

1- we work with a given number of flavours and active RH neutrinos
2-we implement simplified solutions of the Boltzmann equations
3-we check a posteriori that the assumptions in step (1) are correct

Fit procedure

4- in the case of a positive answer, we use the heavy spectrum and the Dirac mass matrix obtained from the fit to solve numerically the Boltzmann equations and get a more precise determination of η_B

We start with:

$$10^9 < M_{\nu_1} < 10^{12}\, GeV$$

τ Yukawa coupling is in equilibrium: two-flavour approach

Blanchet and Di Bari,
JCAP 0703, 018 (2007)
Abada et al.,
JHEP 0609, 010 (2006)

$$(M_{\nu_2} - M_{\nu_1}) / M_{\nu_1} \sim O(1)$$

N_1 and N_2 contribute to leptogenesis

Davidson, Nardi, Nir,
Phys.Rept.466, 105 (2008)

Fit results

- We have to estimate 15 real parameters:

  12 in Md, 2 contained is s and one in r_v

- 15 observables at the GUT scale:

  6 quark masses, 4 in the CKM, 3 in the PMNS, η_B, $\Delta m_{sol}/\Delta m_{atm}$

Obs.	fit	pull	Obs.	fit	pull
mu	0.49	0.03	|Vus|	0.225	0.038
md	0.78	0.75	|Vcb|	0.042	-0.208
ms	32.5	-1.5	|Vub|	0.0038	-0.659
mc	0.287	-1.49	J	3.1×10^{-5}	0.589
mb	1.11	-2.77	$\sin^2\theta_{12}$	0.318	0.611
mt	71.4	0.7	$\sin^2\theta_{23}$	0.353	-1.548
r	0.031	0.1	$\sin^2\theta_{13}$	0.0222	-0.758
η_B	5×10^{-10}	-0.001		$\chi^2_{min} = 17.4$	

Fit results

$$\chi^2_{min} = 17.4$$

- All data reproduced within 3σ
- The largest contribution from the atmospheric angle → This tendency to drift toward smaller values is due to the stringent requirements imposed by η_B (otherwise χ^2 ~0.95)

predictions

Light ν masses (eV)	Heavy ν masses (10^{11} GeV)	Phases (°)	m_{ee} (eV)	Σm_i (eV)
0.0046	1.00	δ=88.6	5×10^{-4}	0.065
0.0098	1.09	ϕ_1=-33.2		
0.0504	21.4	ϕ_2=15.7		

compact RH spectrum

Buccella et al., Phys.Rev.D86, 035012 (2012)

Axions as dark matter particles

- The axion mechanism gives a solution to the strong CP problem without need to impose an additional constraint in the fitting procedure

- mass:

$$m_a = \frac{(m_u/m_d)^{\frac{1}{2}}}{1+m_d/m_d}\,\frac{f_\pi m_\pi}{F_a}$$

Kim and Carosi,
Rev. Mod. Phys. 82 (2010) 557

$\Rightarrow$ $m_a \sim (4.3-4.7)\times 10^{-5}\, eV$

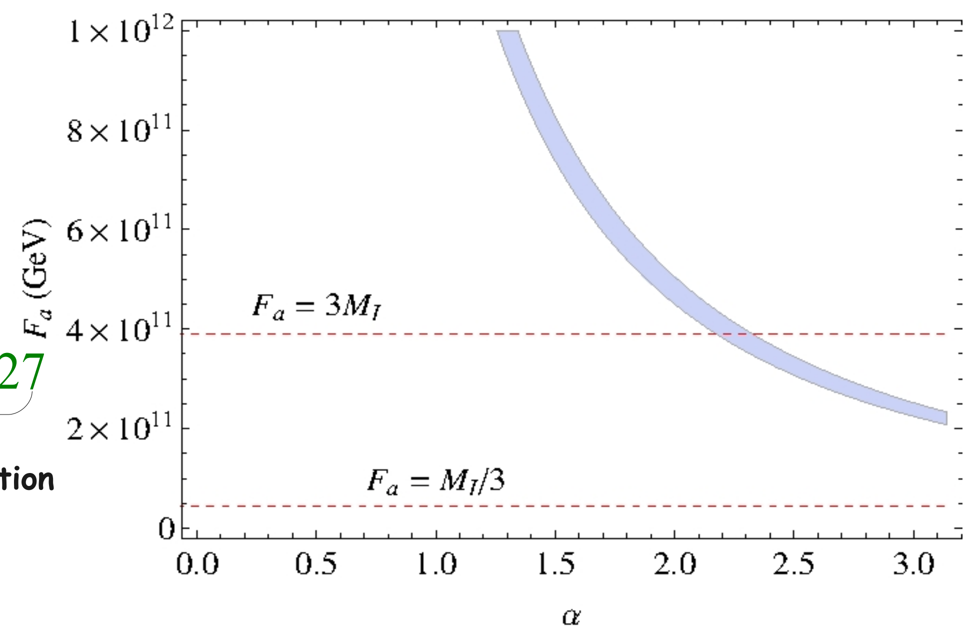
Axion decay constant~ MI

- energy density of cold axions:

$$\Omega_a h^2 \sim 0.7\left(\frac{F_a}{10^{12}\,GeV}\right)^{7/6}\left(\frac{\alpha}{\pi}\right) = 0.1199 \pm 0.0027$$

PLANCK collaboration
arXiv:1303.5076

α=initial misalignment angle



Conclusions

- Non-susy SO(10) gives a viable GUT scenario for beyond SM physics
- A particular breaking chain with $M_I \sim 10^{11}$ GeV is needed to accommodate all compelling phenomena that demand new physics below M_{GUT}
- Price to pay: very large level of fine-tuning !
- Competitive scenarios: non-renormalizable couplings (smaller Higgs representations)

On the SO(10) gauge group

$\mathrm{SO}(10)$:

real $10\,x\,10$ matrices O

$O^T O = 1 \quad \det O = 1$

All fermions unified to one {16} dimensional rep.

$$16 = 5 + 10 + 1$$

right-handed neutrino

$$\begin{pmatrix} u \\ u \\ u \\ d \\ d \\ d \\ \nu \\ e \\ u^c \\ u^c \\ u^c \\ d^c \\ d^c \\ d^c \\ \nu^c \\ e^c \end{pmatrix}$$

A comment on leptogenesis

- Additional decay channels involving the RH gauge bosons and the colour singlets in the (10,1,3)
- Let us consider the W_R

$$\Gamma_{N_1} = \frac{(M^{dag}_{\nu_D} M_{\nu_D})_{11}}{4\pi v_u^2} M_{\nu_1}(1+X)$$

Dilution factor (X)

$$M_{\nu_1} > M_{W_R}$$

NO because 2-body decays

$N \to l\, W_R$ are too fast $\to X \sim O(10^4\text{-}10^5)$

$$M_{\nu_1} < M_{W_R}$$

3-body decays $\to \Gamma_3 < H$ implies

$$M_{\nu_1} > 2\cdot 10^{11} / (M_{W_R} / M_{\nu_1})^4$$

Satisfied for $M_{WR} \sim M_{\nu 1} \sim M_I$

Other breaking chains

$SO(10) \to 3_c 2_L 2_R 1_X \to SM$

(1,2,2,0) in 126 + (1,1,3,0) in 45 → $M_I \sim 10^9$ GeV

[or (1,2,2,-1/2) in 16]

$SO(10) \to 3_c 2_L 2_R 1_X \times P \to SM$

$M_I \sim (0.4\text{-}1)\ 10^{11}$ GeV

$\tau \sim 10^{-1/-2}\ \tau_{exp}$

$3_c 2_L 2_R 1_X$ not a suitable intermediate scale

Extended survival hypothesis

- which is the assumption that at any scale, the only scalar multiplets present are those that develop VEVs at smaller scales

	210	$\overline{126}$	45	10
M_{GUT}	All components	(6,1,1) ($\overline{10}$,3,1)	(1,3,1) (6,2,2) (15,1,1)	(6,1,1)
M_I	_	(10,1,3) (15,2,2)	(1,1,3)	_
EW	-	-	-	(1,2,2)