The Standard Model is very successful but...

- Neutrinos have masses (νSM)
- Dark matter (no viable explanation) - MH? FS?
- Matter / antimatter asymmetry (no viable explanation) - MH? FS?
- Hierarchy problem (fine-tuning between parameters)
- Strong CP problem (fine-tuning between parameters)
- Gauge couplings (additional free parameters) - GUT?
- Flavour problem (many additional free parameters) - FS?

BSM solutions involve additional fields and symmetries, like MH and FS.

The Standard Model

Gauge group: $SU(3)_C \times SU(2)_L \times U(1)_Y$

Chiral spin $1/2$ fermions (left and right)
Quarks: colour triplets of $SU(3)_C$
Left fermions are doublets of $SU(2)_L$
Spin 0 scalar, doublet of $SU(2)_L$

The Standard Model (1 generation)

Gauge group: $SU(3)_C \times SU(2)_L \times U(1)_Y$

Quarks (Q, u_R, d_R): colour triplets of $SU(3)_C$
LH fields (Q and L): doublets of $SU(2)_L$
e_R just $U(1)_Y$
(νSM: add ν_R, complete singlet)

Scalar H also doublet of $SU(2)_L$
$\langle H \rangle$ breaks $SU(2)_L \times U(1)_Y \to U(1)_{em}$

Mass terms: $m_f F_\alpha f_R$ not invariant under $SU(2)_L$

But $y_f(\epsilon^{\alpha\beta} H_\alpha F_\beta) f_R$ is...
$y_f \langle H \rangle F f_R \to m_f F f_R$ with $m_f = y_f \langle H \rangle$

Multi-Higgs models

Gauge group: $SU(3)_C \times SU(2)_L \times U(1)_Y$

Quarks (Q, u_R, d_R): colour triplets of $SU(3)_C$
LH fields (Q and L): doublets of $SU(2)_L$
e_R just $U(1)_Y$
(νSM: add ν_R, complete singlet)

Scalars H_i, doublets of $SU(2)_L$
Potential $V(H_i)$, Yukawa couplings, with each H_i...
Proliferation of parameters? Symmetries!

The Standard Model (3 generations)

Gauge group: $SU(3)_C \times SU(2)_L \times U(1)_Y$

Quarks (Q^i, u_R^j, d_R^k): colour triplets of $SU(3)_C$
LH fields (Q^i and L^i): doublets of $SU(2)_L$
e_R^j just $U(1)_Y$
(νSM: add ν_R^k, complete singlet)

Scalar H also doublet of $SU(2)_L$
$\langle H \rangle$ breaks $SU(2)_L \times U(1)_Y \to U(1)_{em}$

Mass terms: $M_{ij} F_\alpha^i f_R^j$ not invariant under $SU(2)_L$

But $Y_{ij}(\epsilon^{\alpha\beta} H_\alpha F_\beta^i) f_R^j$ is...
$Y_{ij}\langle H \rangle F^i f_R^j \to M_{ij} F^i f_R^j$
Proliferation of parameters? Symmetries!

Papers with PhD student Miguel Levy

Revisiting the Universal Texture Zero of Flavour: a Markov Chain Monte Carlo Analysis #1

Jordan Bernigaud (KIT, Karlsruhe and KIT, Karlsruhe, TTP), Ivo de Medeiros Varzielas (Lisbon, CFTP), Miguel Levy (Lisbon, CFTP), Jim Talbert (Cambridge U., DAMTP) (Nov 28, 2022)

e-Print: 2211.15700 [hep-ph]

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Ivo de Medeiros Varzielas (Lisbon, CFTP), Steve F. King (Southampton U.), Miguel Levy (Lisbon, CFTP) (Nov 1, 2022)

Published in: *JHEP* 02 (2023) 143 • e-Print: 2211.00654 [hep-ph]

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Ivo de Medeiros Varzielas (Lisbon, CFTP), Igor P. Ivanov (Zhongshan U., Zhuhai), Miguel Levy (Lisbon, CFTP) (Jul 17, 2021)

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Ivo de Medeiros Varzielas (Lisbon, CFTP), Miguel Levy (Lisbon, CFTP), Ye-Ling Zhou (Southampton U.) (Aug 12, 2020)

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Regular Article - Theoretical Physics | Open Access | Published: 07 May 2022

Softly-broken A_4 or S_4 3HDMs with stable states

Ivo de Medeiros Varzielas & Diogo Ivo

The European Physical Journal C **82**, Article number: 415 (2022) | Cite this article

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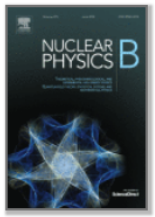

Two A4 modular symmetries for Tri-Maximal 2 mixing

Ivo de Medeiros Varzielas ✉, João Lourenço ✉

CFTP, Departamento de Física, Instituto Superior Técnico, Universidade de Lisboa, Avenida Rovisco Pais 1, 1049 Lisboa, Portugal

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Multi-Higgs and Flavour with symmetries

Conclusion

- Models with Multi-Higgs and symmetries are a very natural extension of the Standard Model
- Models with Family Symmetry are a very natural extension of the Standard Model
- Viable research opportunities for interested students