W Boson Mass and Grand Unification via Type-II Seesaw-like Mechanism

Yusuke Shimizu (Niigata University → Kaishi Professional University)

24th Jan. 2024

Hirschfest, 23th - 24th Jan. 2024, Short Talk@IFIC

Congratulations!!

碁：Go

Martin is the excellent “Go” player.

“黒先”

The pronunciation is “Kuro-Saki”.
Meaning is “The player with the black stones makes the first move”.

Out line

1. Visiting for Valencia

2. Recent Interest

3. Our Model

4. Summary

1. Visiting for Valencia

- Summer Institute 2009 (13th - 20th Aug. 2009) @Fuji-Yoshida

Aug.15(Sat)

9:00-10:20	Martin Hirsch (U. of Valencia)	Neutrino mass models and LHC

1. Visiting for Valencia

The first visit !

- Seminar (10th Mar. 2010) @IFIC

ASTROPARTICLES
Astroparticles and High Energy Physics Group

SEMINARS OF 2010

Tri-bimaximal Mixing and Cabibbo Angle in S_4 Flavor Model with SUSY

Dr. Yusuke Shimizu

U Nigata, Japan

Sala de Juntas del IFIC Paterna

Wednesday, March 10th, 2010 at 11:00

Abstract

We present an S_4 flavor model to unify quarks and leptons in the framework of the SU(5) SUSY GUT.
Taking vacuum alignments of relevant gauge singlet scalars, we predict the quark mixing as well as the tri-bimaximal mixing of neutrino flavors.
Especially, the Cabibbo angle is predicted to be 15 degree in the limit of the vacuum alignment.
Considering the next leading order, we predict the deviation from the tri-bimaximal mixing.
Flavor symmetry also constraints the sleptons structure, then we discuss the FCNC.

1. Visiting for Valencia

- FLASY11 (11th - 14th Jul. 2011) @ IFIC

The second visit !!

Proceedings of the 1^{st} workshop on Flavor Symmetries and consequences in Accelerators and Cosmology (FLASY2011)

Editors:
M. Hirsch[a], D. Meloni[b], S. Morisi[a], S. Pastor[a], E. Peinado[a], J.W.F. Valle[a]
Authors:
Adisorn Adulpravitchai[c], D. Aristizabal Sierra[d], F. Bazzocchi[e], Gautam Bhattacharyya[f], G. Blankenburg[b], M. S. Boucenna[a], I. de Medeiros Varzielas[g], Marco Aurelio Diaz[h], Gui-Jun Ding[i], J. N. Esteves[j], Yasaman Farzan[k], Sebastian Garcia Saenz[h], W. Grimus[l], Claudia Hagedorn[m], J. Jones-Perez[n], Anjan S. Joshipura[y], Avihay Kadosh[o], Kenji Kadota[q], Sin Kyu Kang[p], Joern Kersten[q], Benjamin Koch[h], Martin B. Krauss[s], Philipp Leser[g], Patrick Otto Ludl[l], Vinzenz Maurer[t], Luca Merlo[u,v], Grigoris Panotopoulos[w], A. Papa[z], Heinrich Pas[g], Ketan M. Patel[y], Werner Rodejohann[c], U. J. Saldaña Salazar[ab], H. Serodio[ac], Yusuke Shimizu[ad], Martin Spinrath[c], Emmanuel Stamou[u,v,ae], Hiroaki Sugiyama[af], M. Taoso[ag,ah], Takashi Toma[c,ai], Liliana Velasco-Sevilla[r].

1. Visiting for Valencia

- We published two papers

PHYSICAL REVIEW D **84**, 036003 (2011)

Relating quarks and leptons without grand unification

S. Morisi,[1,*] E. Peinado,[1,†] Yusuke Shimizu,[2,‡] and J. W. F. Valle[1,§]

[1]*AHEP Group, Institut de Física Corpuscular — CSIC/Universitat de València, Edificio Institutos de Paterna, Apt. 22085, E-46071 Valencia, Spain*

[2]*Graduate School of Science and Technology, Niigata University, Niigata 950-2181, Japan*

(Received 13 April 2011; published 2 August 2011)

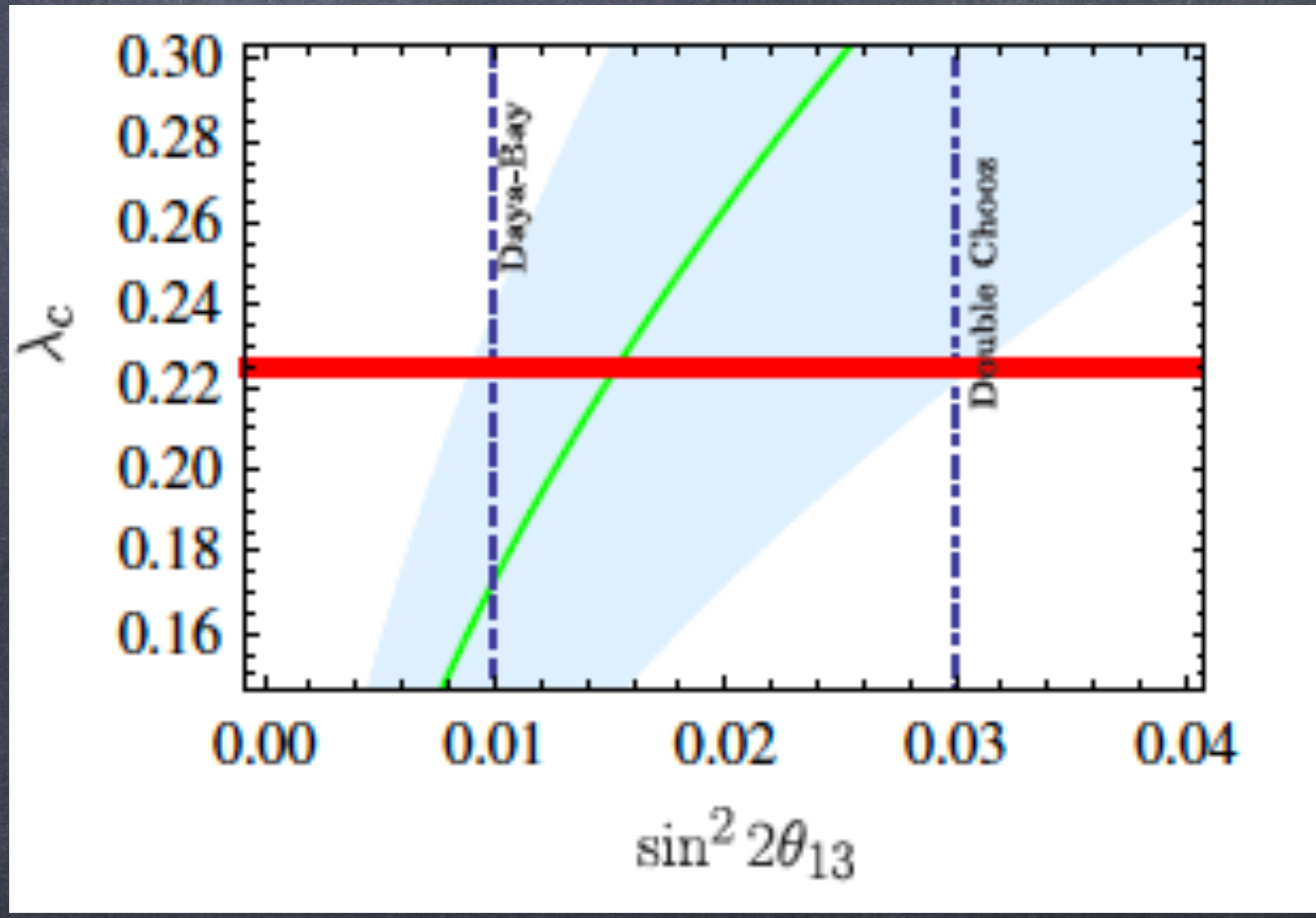
In combination with supersymmetry, flavor symmetry may relate quarks with leptons, even in the absence of a grand-unification group. We propose an $SU(3) \times SU(2) \times U(1)$ model where both supersymmetry and the assumed A_4 flavor symmetries are softly broken, reproducing well the observed fermion mass hierarchies and predicting: (i) a relation between down-type quarks and charged lepton masses, and (ii) a correlation between the Cabibbo angle in the quark sector and the reactor angle θ_{13} characterizing CP violation in neutrino oscillations.

$$\frac{m_\tau}{\sqrt{m_e m_\mu}} \approx \frac{m_b}{\sqrt{m_d m_s}},$$

$$\lambda_C \approx \frac{1}{\sqrt{2}} \frac{m_\mu m_b}{m_\tau m_s} \sqrt{\sin^2 2\theta_{13}} - \sqrt{\frac{m_u}{m_c}},$$

ACKNOWLEDGMENTS

We thank M. Hirsch and M. Tanimoto for useful discussions. This work was supported by the Spanish MICINN under Grants No. FPA2008-00319/FPA and MULTIDARK CSD2009-00064, by Prometeo/2009/091 (Generalitat valenciana), by the EU Network Grant No. UNILHC PITN-GA-2009-237920. S. M. is supported by a Juan de la Cierva contract, E. P. is supported by CONACyT (Mexico), and Y. S. by the Japan Society of Promotion of Science, Grant-in-Aid for Scientific Research, No. 22.3014.



1. Visiting for Valencia

- We published two papers

PHYSICAL REVIEW D **86**, 073008 (2012)

Predictive discrete dark matter model and neutrino oscillations

M. S. Boucenna,* S. Morisi,† E. Peinado,‡ and J. W. F. Valle§
Astroparticle and High Energy Physics Group, Instituto de Física Corpuscular—C.S.I.C./Universitat de València Edificio de Institutos de Paterna, Apartado 22085, E-46071 València, Spain

Yusuke Shimizu‖
Department of Physics, Niigata University, Niigata 950-2181, Japan
(Received 21 May 2012; published 16 October 2012)

Dark matter stability can be achieved through a partial breaking of a flavor symmetry. In this framework we propose a type-II seesaw model where left-handed matter transforms nontrivially under the flavor group $\Delta(54)$, providing correlations between neutrino oscillation parameters, consistent with the recent Daya-Bay and RENO reactor angle measurements, as well as lower bounds for neutrinoless double beta decay. The dark matter phenomenology is provided by a Higgs-portal.

We thank Luis Dorame, Luis Lavoura, and Martin Hirsch for discussions and interesting comments. This work was supported by the Spanish MINECO under Grant No. FPA2011-22975 and MULTIDARK CSD2009-00064 (Consolider-Ingenio 2010 Programme), by Prometeo/2009/091 (Generalitat Valenciana), and by the EU ITN UNILHC PITN-GA-2009-237920. Y. S. is supported by Grand-in-Aid for Scientific Research, No. 22.3014 in JSPS.

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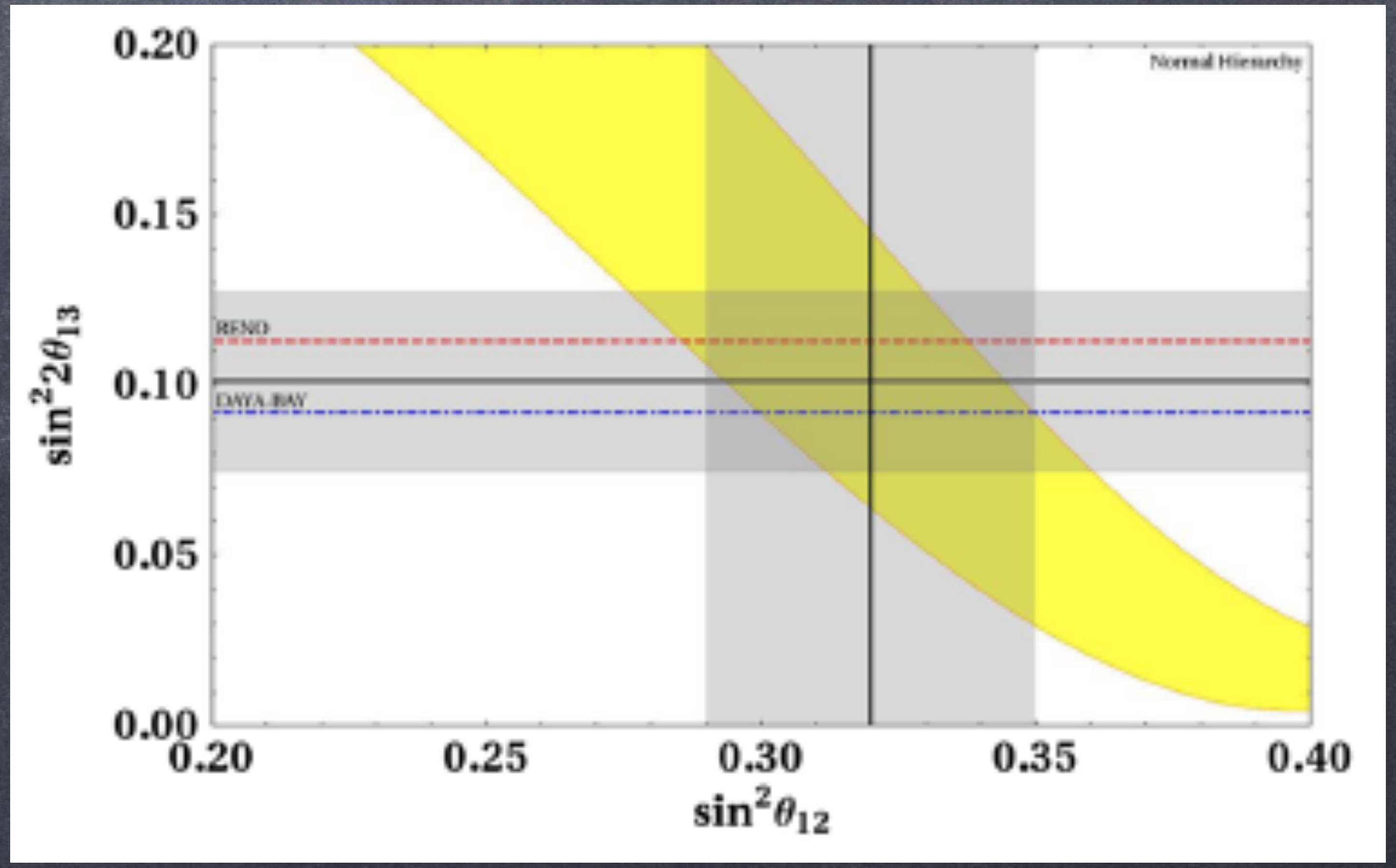

PHYSICAL REVIEW D **82**, 116003 (2010)

Discrete dark matter

M. Hirsch,* S. Morisi,† E. Peinado,‡ and J. W. F. Valle§

1. Visiting for Valencia

- We published two papers

PHYSICAL REVIEW D **86,** 073008 (2012)

Predictive discrete dark matter model and neutrino oscillations

M. S. Boucenna,[*] S. Morisi,[†] E. Peinado,[‡] and J. W. F. Valle[§]
Astroparticle and High Energy Physics Group, Instituto de Física Corpuscular—C.S.I.C./Universitat de València Edificio de Institutos de Paterna, Apartado 22085, E-46071 València, Spain

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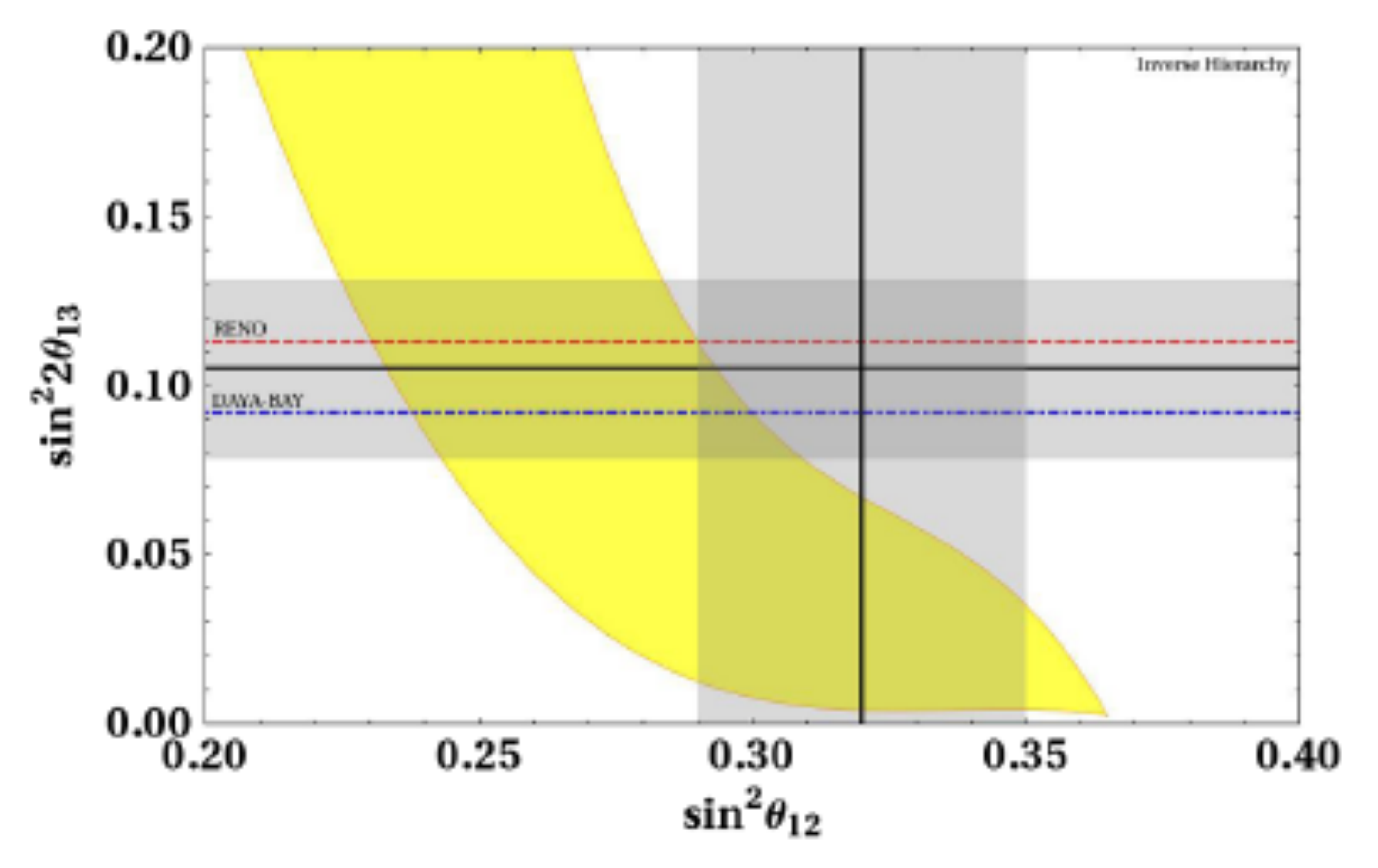


PHYSICAL REVIEW D **82,** 116003 (2010)

Discrete dark matter

M. Hirsch,[*] S. Morisi,[†] E. Peinado,[‡] and J. W. F. Valle[§]

1. Visiting for Valencia

- FestiValle (26th Jul. 2013) @ IFIC

Quark-lepton mass relations from modular flavor symmetry

Mu-Chun Chen,[1,*] Stephen F. King,[2,†] Omar Medina,[3,‡] and José W. F. Valle[3,§]

[1] *Department of Physics and Astronomy, University of California, Irvine, CA 92697-4575 USA*

[2] *School of Physics and Astronomy, University of Southampton, Southampton SO17 1BJ, United Kingdom*

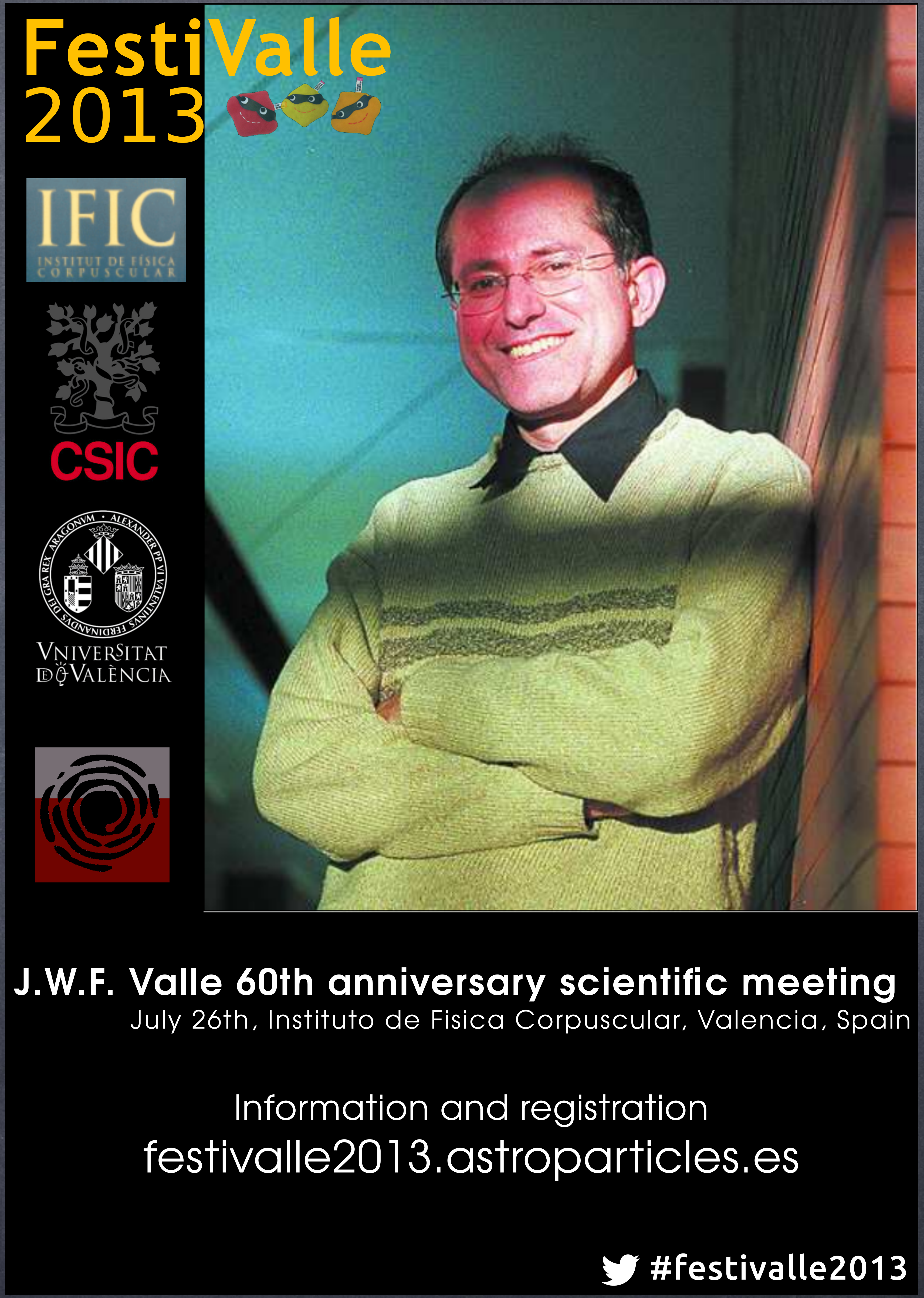
[3] *Instituto de Física Corpuscular (IFIC), Universidad de Valencia-CSIC, Paterna (Valencia) E-46980, Spain*

The so-called Golden Mass Relation provides a testable correlation between charged-lepton and down-type quark masses, that arises in certain flavor models that do not rely on Grand Unification. Such models typically involve broken family symmetries. In this work, we demonstrate that realistic fermion mass relations can emerge naturally in modular invariant models, without relying on *ad hoc* flavon alignments. We provide a model-independent derivation of a class of mass relations that are experimentally testable. These relations are determined by both the Clebsch-Gordan coefficients of the specific finite modular group and the expansion coefficients of its modular forms, thus offering potential probes of modular invariant models. As a detailed example, we present a set of viable mass relations based on the $\Gamma_4 \cong S_4$ symmetry, which have calculable deviations from the usual Golden Mass Relation.

$$\frac{m_s m_d}{m_b (m_b \pm 3m_s)} \approx \frac{m_\mu m_e}{m_\tau (m_\tau \pm 3m_\mu)}.$$

arXiv:2312.09255

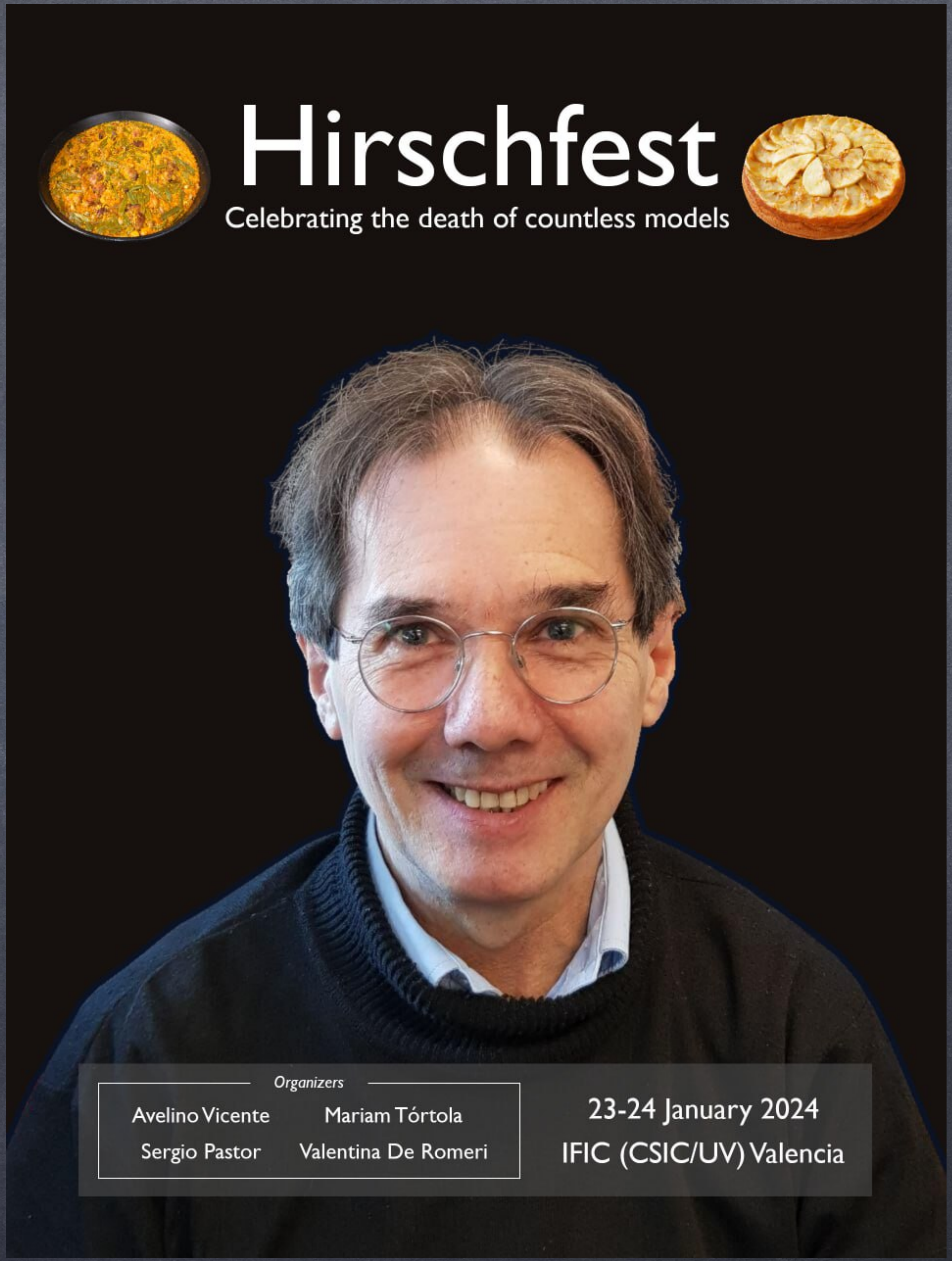
The third visit !!!



1. Visiting for Valencia

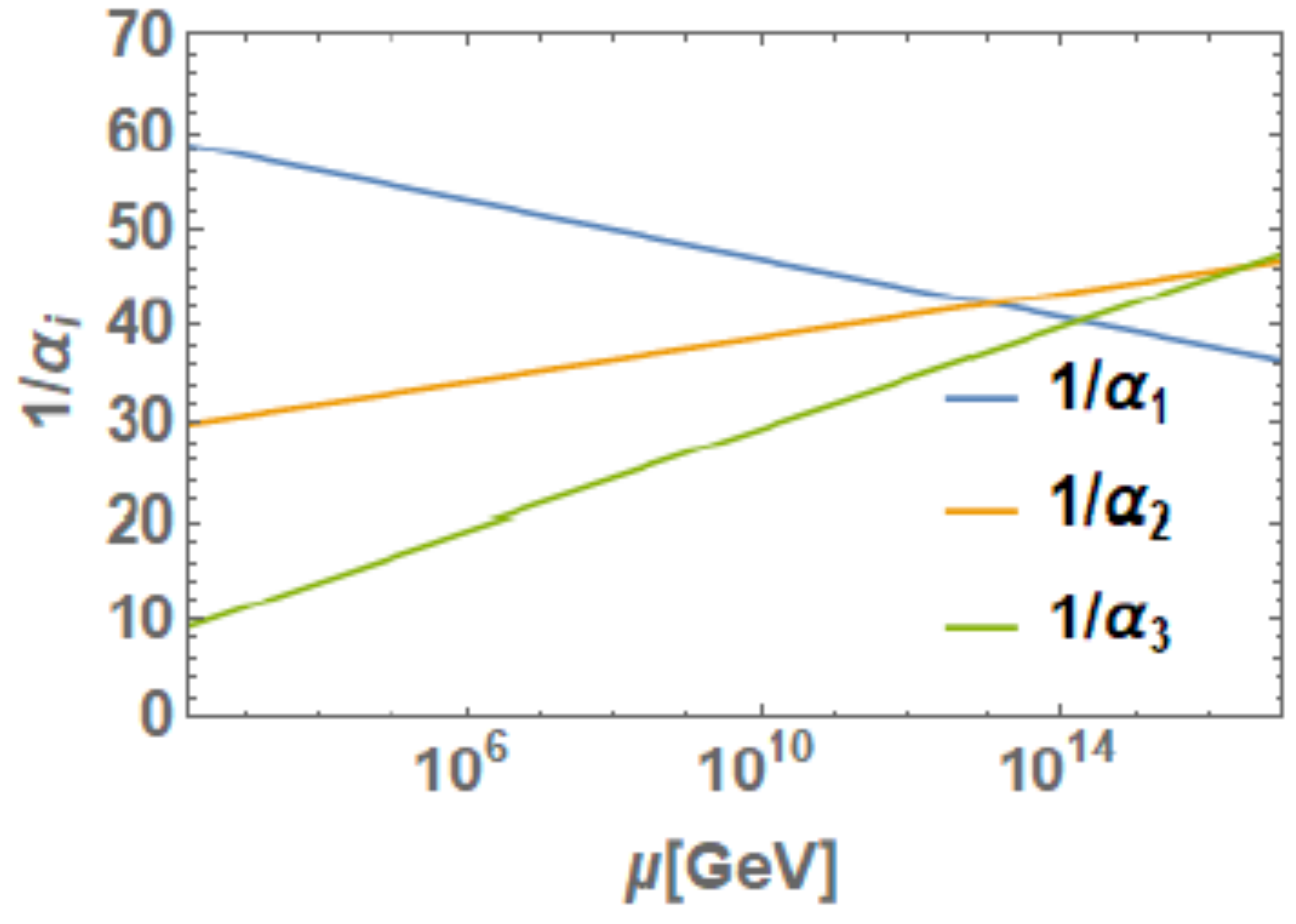
- Hirschfest (23rd - 24th Jan. 2024) @ IFIC

The fourth visit !!!!



2. Recent Interest

- Gauge coupling unification



Blue line : U(1) gauge coupling
Orange line : SU(2) gauge coupling
Green line : SU(3) gauge coupling

- The CDF collaboration reported the W boson mass anomaly

J. de Blas, M. Pierini, L. Reina and L. Silvestrini, Phys.Rev.Lett. 129 (2022) 27, 271801

$$M_W^{\mathrm{SM}} = 80.3500 \pm 0.0056 \text{ GeV}$$

$6.5\ \sigma$

$$M_W^{\mathrm{CDF}} = 80.4335 \pm 0.0094 \text{ GeV}$$

[CDF Collaboration], Science 376, no.6589, 170-176 (2022)

- The average of the W boson mass:

$$M_W^{\mathrm{exp}} = 80.4133 \pm 0.0080 \text{ GeV}.$$

J. de Blas, M. Pierini, L. Reina and L. Silvestrini, Phys.Rev.Lett. 129 (2022) 27, 271801

2. Recent Interest

We focus on the real SU(2) triplet scalar in order to explain the W boson anomaly.

$$24_H = \begin{pmatrix} \Sigma_8 - \frac{2}{\sqrt{30}}\Sigma_0 & \Sigma_{(\bar{3},2)} \\ \Sigma_{(3,2)} & \Sigma_3 + \frac{3}{\sqrt{30}}\Sigma_0 \end{pmatrix}$$

$$\Sigma_8 \sim (8,1,0), \quad \Sigma_3 \sim (1,3,0), \quad \Sigma_0 \sim (1,1,0),$$
$$\Sigma_{(3,2)} \sim (3,2,-5/6), \quad \Sigma_{(\bar{3},2)} \sim (\bar{3},2,5/6).$$

2. Recent Interest

R. S. Chivukula, N. D. Christensen, and E. H. Simmons, Phys. Rev. D 77, 035001 (2008)

P. Fileviez Perez, H. H. Patel and A. D. Plascencia, Phys. Lett. B 833 (2022), 137371

SM Higgs and real SU(2) triplet Higgs (Y=0)

$$H = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \sim (1, 2, 1/2) \qquad T = \frac{1}{2}\begin{pmatrix} T^0 & \sqrt{2}T^+ \\ \sqrt{2}T^- & -T^0 \end{pmatrix} \sim (1, 3, 0)$$

Lagrangian for the Higgs sector :

$$\mathcal{L}_{\text{scalar}} = (D_\mu H)^\dagger (D^\mu H) + \mathrm{Tr}(D_\mu T)^\dagger (D^\mu T) - V(H, T)$$

$$D_\mu H = \partial_\mu H + i g_1 \frac{B_\mu}{2} + i g_2 W_\mu, \quad D_\mu T = \partial_\mu T + i\, g_2 \left[W_\mu, T \right]$$

2. Recent Interest

Lagrangian for the Higgs sector：

$$\mathcal{L}_{\mathrm{scalar}} = (D_\mu H)^\dagger (D^\mu H) + \mathrm{Tr}(D_\mu T)^\dagger (D^\mu T) - V(H,T)$$

$$\begin{aligned} &V(H,T) \\ &= -m_h^2 H^\dagger H + \lambda_0 (H^\dagger H)^2 + M_T^2 \mathrm{Tr}[T^2] + \lambda_1 \mathrm{Tr}[T^4] + \lambda_2 (\mathrm{Tr}[T^2])^2 \\ &+ \alpha (H^\dagger H) \mathrm{Tr}[T^2] + \beta H^\dagger T^2 H + \mu H^\dagger T H \end{aligned}$$

Higgs fields take the VEVs：v_h ,v_T

$$H = \begin{pmatrix} \phi^+ \\ (v_h + h^0 + iG^0)/\sqrt{2} \end{pmatrix}, \qquad T = \frac{1}{2} \begin{pmatrix} v_T + t^0 & \sqrt{2} t^+ \\ \sqrt{2} t^- & -v_T - t^0 \end{pmatrix}.$$

$(t^- = (t^+)^*)$

2. Recent Interest

W boson mass：

$$M_W^2 = \left(M_W^{\mathrm{SM}}\right)^2 + g_2^2 v_T^2$$

$$v_T = 4.85\ \mathrm{GeV}.$$

J. de Blas, M. Pierini, L. Reina and L. Silvestrini, Phys.Rev.Lett. 129 (2022) 27, 271801

$$M_W^{\mathrm{SM}} = 80.3500 \pm 0.0056\ \mathrm{GeV}$$

6.5 σ

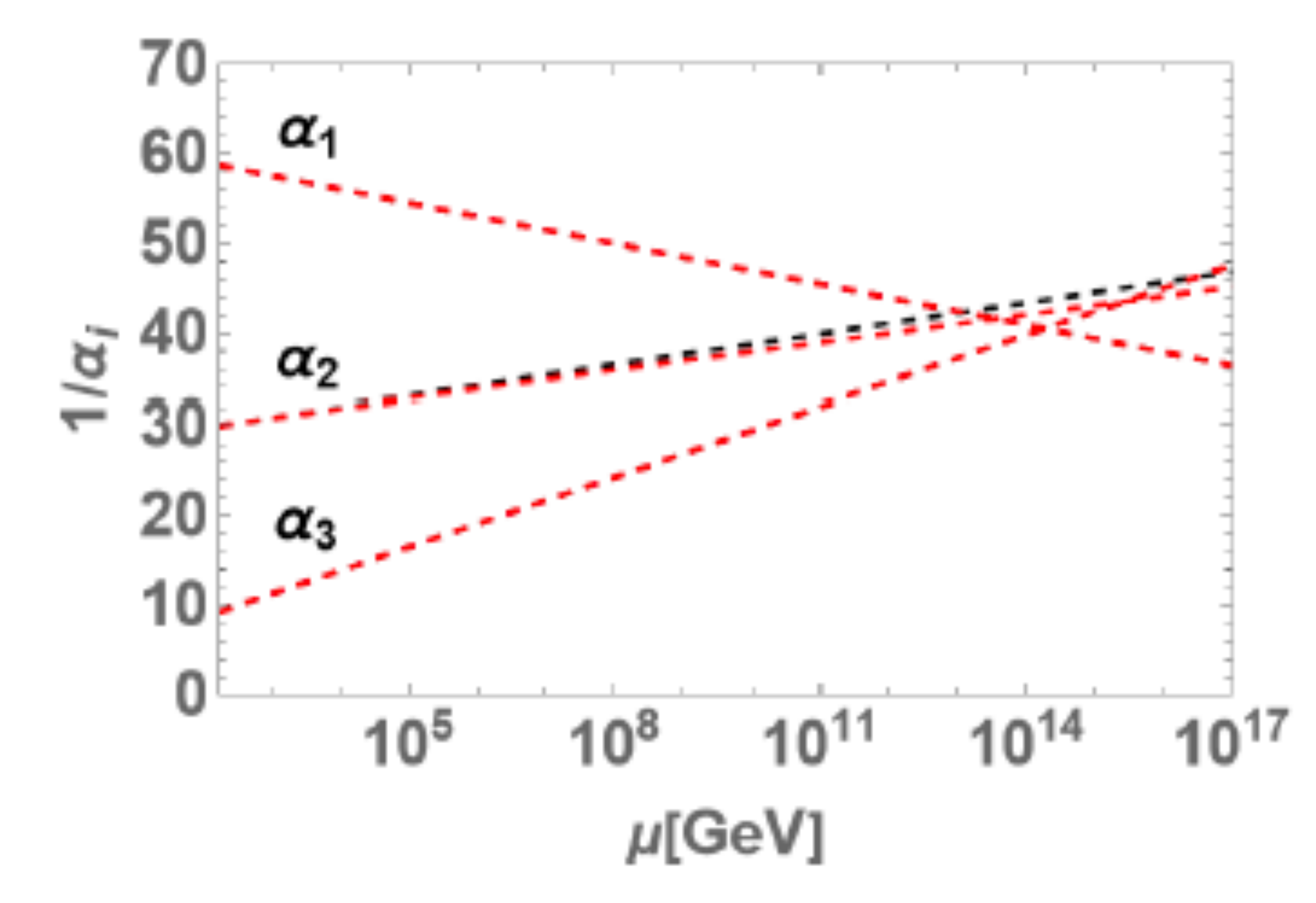
$$M_W^{\mathrm{exp}} = 80.4133 \pm 0.0080\ \mathrm{GeV}$$

2. Recent Interest

- Gauge coupling unification

J. L. Evans, T. T. Yanagida and N. Yokozaki, Phys. Lett. B 833 (2022), 137306

The real SU(2) triplet scalar contribute only SU(2) gauge coupling



black : SM

red : real triplet Higgs

The gauge couplings are not unified.

3. Our Model

Y.S. and S. Takeshita, Nucl. Phys. B 994 (2023) 116290

We introduce vector-like fermions in addition to the minimal SU(5) GUT model.

$\overline{\mathbf{5}}^i_L$, $\mathbf{10}^i_L$, A_μ, $\mathbf{5}_\mathrm{H}$, $\mathbf{24}_\mathrm{H}$

$\boxed{10^{4,5}_{L,R}}$

Vector-like fermions:

$$10^{4,5}_{L,R} = Q(3,2,1/6) \oplus U^c(\bar{3},1,-2/3) \oplus E^c(1,1,1).$$

3. Our Model

Y.S. and S. Takeshita, Nucl. Phys. B 994 (2023) 116290

- Yukawa interaction for SM fermions :

$$\mathcal{L}_{\rm SM} \supset \sum_{i,j=1}^{3} \left[Y_1^{ij} 5_{\rm H} 10_L^i 10_L^j \right] + \sum_{i,j=1}^{3} \left[Y_2^{ij} 5_{\rm H}^* \overline{5}_L^i 10_L^j \right] + \text{h.c.}$$

- Yukawa interaction for vector-like fermions :

$$\mathcal{L}_{\rm VL} \supset \overline{10}_L^4 [Y_{10}^4 24_H + M_{10}^4] 10_R^4 + \overline{10}_L^5 [Y_{10}^5 24_H + M_{10}^5] 10_R^5 + \text{h.c.}$$

In order to forbid the SM particles and vector-like fermion interactions, we introduce $\mathbb{Z}_3$ symmetry.

3. Our Model

Y.S. and S. Takeshita, Nucl. Phys. B 994 (2023) 116290

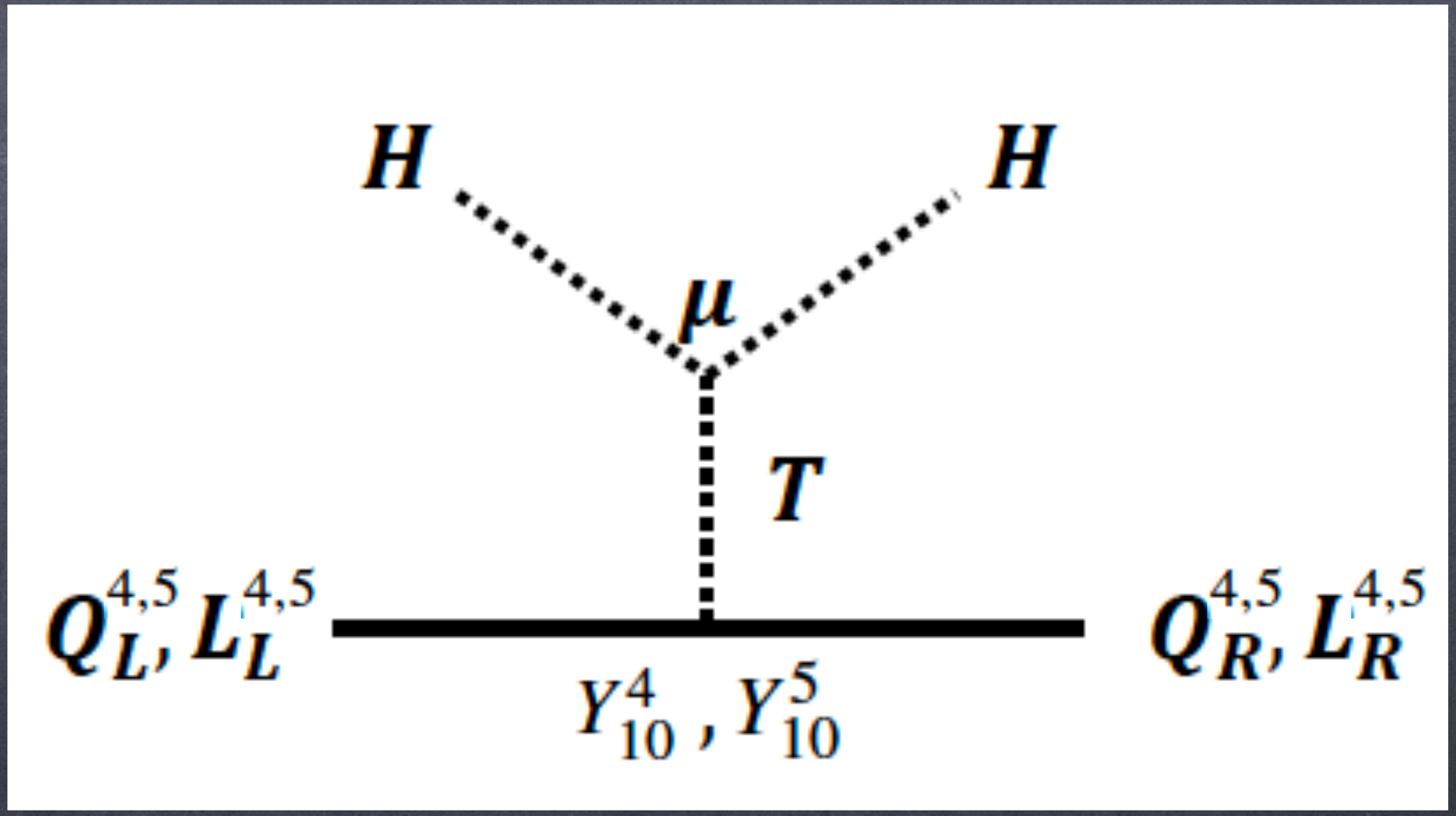
- Yukawa interaction for vector-like fermions：

$$\mathcal{L}_{\mathrm{VL-RT}} \supset Y_{10}^{4} T \bar{Q}_L^4 Q_R^4 + Y_{10}^{5} T \bar{Q}_L^5 Q_R^5 + \mathrm{h.c.}$$

- Seesaw mechanism:
  (type-II：SU(2) triplet boson)

  Schechter, Valle '80, Mohapatra, Senjanovic '81

$$T = \frac{1}{2}\begin{pmatrix} v_T + t^0 & \sqrt{2}t^+ \\ \sqrt{2}t^- & -v_T - t^0 \end{pmatrix}, \quad v_T \approx \frac{\mu v_h^2}{4M_T^2}$$



3. Our Model

Y.S. and S. Takeshita, Nucl. Phys. B 994 (2023) 116290

The scalar mass eigenvalues：

$$v_h \gg v_T,\ \theta_0 \ll 1.$$

$$M_h^2 = 2\lambda_0 v_h^2, \longleftarrow \text{the SM-like Higgs}$$

$$M_H^2 = B v_T^2 + \frac{\mu v_h^2}{4 v_T},$$

$$M_{H^\pm}^2 = \mu v_T + \frac{\mu v_h^2}{4 v_T}.$$

$$\xrightarrow{v_h \gg v_T} \boxed{M_H^2 = M_{H^\pm}^2 \approx \frac{\mu v_h^2}{4 v_T} (= M_T^2)}$$

$$\tan 2\theta_0 = \frac{4 v_h v_T(-\mu + 2A v_T)}{8\lambda_0 v_h^2 v_T - 4B v_T^3 - \mu v_h^2},$$

$$\tan 2\theta_+ = \frac{4 v_h v_T}{4 v_T^2 - v_h^2}.$$

3. Our Model

Y.S. and S. Takeshita, Nucl. Phys. B 994 (2023) 116290

- Vector-like fermion masses :

$$M_Q^4 = M_{10}^4 - \frac{Y_{10}^4}{4\sqrt{15}}V + \boxed{Y_{10}^4\frac{\mu v_h^2}{8M_T^2}},$$

$$M_U^4 = M_{10}^4 + \frac{Y_{10}^4}{\sqrt{15}}V,$$

$$M_E^4 = M_{10}^4 - \frac{3Y_{10}^4}{2\sqrt{15}}V,$$

$$M_Q^5 = M_{10}^5 - \frac{Y_{10}^5}{4\sqrt{15}}V + \boxed{Y_{10}^5\frac{\mu v_h^2}{8M_T^2}},$$

$$M_U^5 = M_{10}^5 + \frac{Y_{10}^5}{\sqrt{15}}V,$$

$$M_E^5 = M_{10}^5 - \frac{3Y_{10}^5}{2\sqrt{15}}V.$$

Type-II seesaw-like mechanism

3. Our Model

Y.S. and S. Takeshita, Nucl. Phys. B 994 (2023) 116290

- Vector-like fermion masses：

$$M_Q^4 = M_{10}^4 - \frac{Y_{10}^4}{4\sqrt{15}}V + Y_{10}^4\frac{\mu v_h^2}{8M_T^2},$$

$$M_U^4 = M_{10}^4 + \frac{Y_{10}^4}{\sqrt{15}}V,$$

$$M_E^4 = M_{10}^4 - \frac{3Y_{10}^4}{2\sqrt{15}}V.$$

$$\xrightarrow{\quad M_{10}^4 \approx \frac{Y_{10}^4}{4\sqrt{15}}V \quad}$$

$$\boxed{\begin{aligned} M_Q^4 &= Y_{10}^4\frac{\mu v_h^2}{8M_T^2}, \\ M_U^4 &= M_E^4 = \frac{5Y_{10}^4}{4\sqrt{15}}V. \end{aligned}}$$

3. Our Model

Y.S. and S. Takeshita, Nucl. Phys. B 994 (2023) 116290

- Vector-like fermion masses :

R. S. Chivukula, N. D. Christensen and E. H. Simmons, Phys. Rev. D 77 (2008), 035001

$$M_H, M_{H^\pm} \le \frac{2\sqrt{\pi} v_h^2}{v_T} \longrightarrow \mu < \frac{16\pi v_h^2}{v_T}$$

$$M_H^2 = M_{H^\pm}^2 \approx \frac{\mu v_h^2}{4 v_T}$$

$$M_Q^4 = Y_{10}^4 \frac{\mu v_h^2}{8 M_T^2}$$

$$v_h = \left(\sqrt{2} G_F\right)^{-1/2} \approx 246.22\ \text{GeV}$$

$$v_T = 4.85\ \text{GeV}$$

$$\boxed{M_Q^4 \times (M_T)^2 < 4.76 \times Y_{10}^4\ (\text{TeV})^3}$$

3. Our Model

Y.S. and S. Takeshita, Nucl. Phys. B 994 (2023) 116290

The experimental constraints

- Vector-like quark masses :

A. M. Sirunyan et al. [CMS], Eur. Phys. J. C 79 (2019), 90

$$M_Q^4 > 1660 \text{ GeV}$$

- Charged Higgs masses :

G. Aad et al. [ATLAS], JHEP 06 (2021), 145

$$M_{H^\pm} > 1000 \text{ GeV}$$

- Heavy nutral Higgs masses :

G. Aad et al. [ATLAS], Phys. Rev. D 102 (2020) no.3, 032004

$$M_H > 1400 \text{ GeV}$$

3. Our Model

Y.S. and S. Takeshita, Nucl. Phys. B 994 (2023) 116290

Allowed region for the mass

- Theoretical limit : $M_Q^4 \times (M_T)^2 < 4.76\,(\mathbf{TeV})^3 \;(\,Y_{10}^4 = \mathbf{1})$

$M_Q^4 > 1660$ GeV

$M_H > 1400$ GeV
$(M_{H^\pm} > 1000$ GeV$)$

$M_T = M_H = M_{H^\pm} < 1693$ GeV

$M_Q^4 < 2428$ GeV

$M_Q^4 < 4759$ GeV

$1660 < M_Q^4 < 2428$ GeV, $1400 < M_T < 1693$ GeV, heavy neutral Higgs boson limit
$1660 < M_Q^4 < 4759$ GeV, $1000 < M_T < 1693$ GeV, charged Higgs boson limit

3. Our Model

Y.S. and S. Takeshita, Nucl. Phys. B 994 (2023) 116290

Gauge coupling unification

$$M_Q^4 = 2000\ \mathrm{GeV},\quad M_T = 1500\ \mathrm{GeV},$$

$$M_U^5 = M_{H_8} = 10^8\ \mathrm{GeV}$$

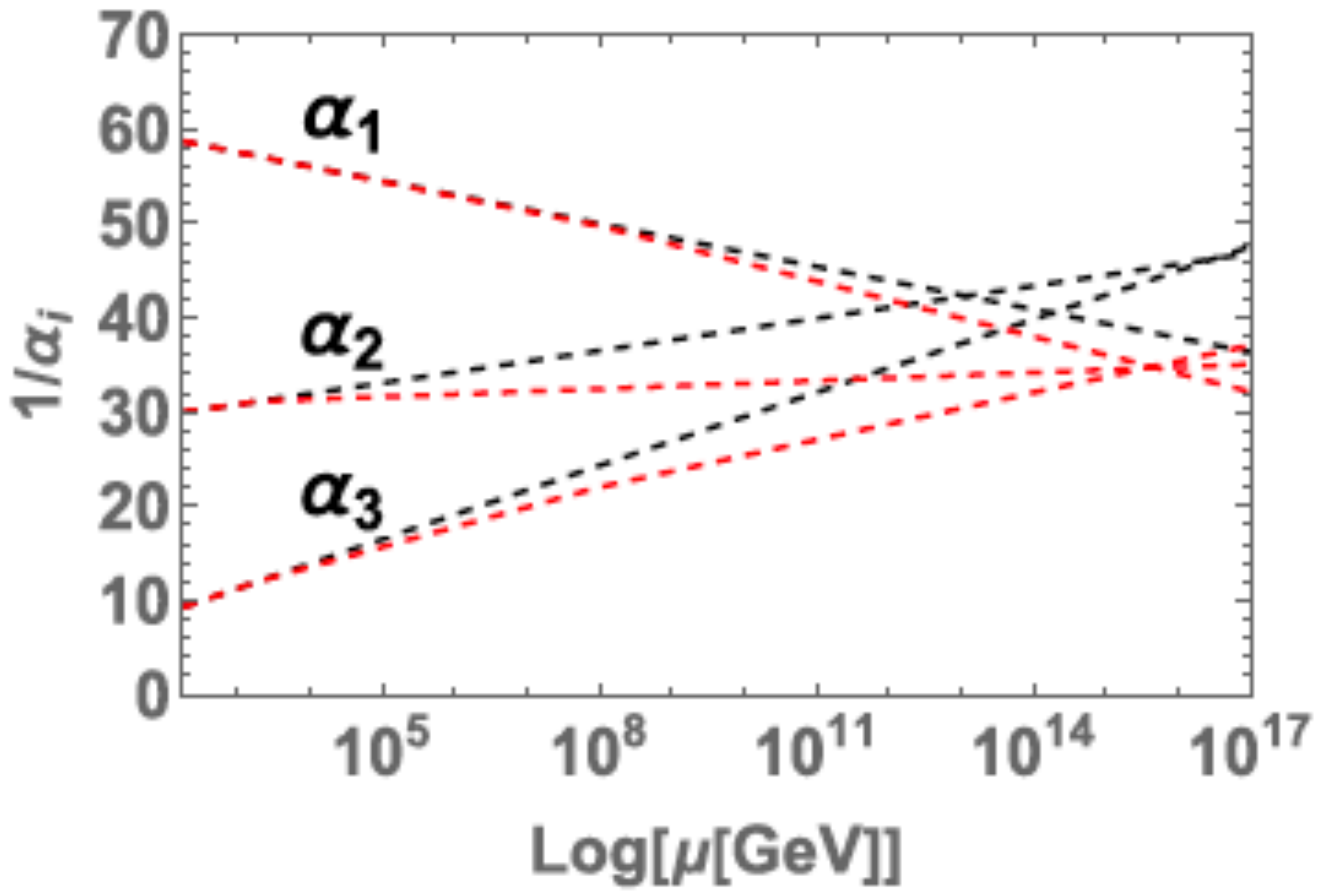
$$M_{\mathrm{GUT}} \approx 5.1 \times 10^{15}\ \mathrm{GeV}$$

$$\alpha_{\mathrm{GUT}} = \alpha_1 = \alpha_2 = \alpha_3 \approx 1/34.7$$

$$\tau_p(p \to \pi^0 e^+) \approx \frac{1}{\alpha_{\mathrm{GUT}}^2}\frac{M_{\mathrm{GUT}}^4}{m_p^5}$$

$$\approx 4.12 \times 10^{34}\ \text{years}$$

P. Nath and P. Fileviez Perez, Phys. Rept. 441 (2007), 191-317



Black : the SM
Red : Our model

4. Summary

- We propose an SU(5) model with Vector-like fermions.

- Vector-like fermions get the masses through the type-II seesaw-like mechanism.

- Thanks for the additional vector-like quarks and SU(2) triplet scalar, the gauge coupling is unified.

- The CDF collaboration W boson mass anomaly is explained by using the VEV of a real SU(2) triplet scalar coming from the 24 representation Higgs.

Congratulations!!

Martin’s 60th birthday