Vector-Like fermions and Z’ as candidates for New Physics

Daniele Rizzo

Based on

arXiv:2209.07971

in collaboration with

A. Chikkaballi
K. Kowalska
W. Kotlarski
E. Sessolo

&

arXiv:2211.XXXXX

in collaboration with

A. E. Cárcamo Hernández
K. Kowalska
H. Lee

NARODOWE CENTRUM NAUKI

NATIONAL CENTRE FOR NUCLEAR RESEARCH ŚWIERK

Supervisor: Kamila Kowalska

03/11/2022

Outline

- **The Standard Model**
  - Theoretical problems of the Standard Model
  - Phenomenological problems of the Standard Model

- **Results from arXiv:2209.07971**

- **Type-II next-to-2HDM**
  - Details on the model
  - The seesaw mechanism
  - Observable: Analytical and Numerical machinery
  - Preliminary results

daniele.rizzo@ncbj.gov.pl
Daniele Rizzo

Outline

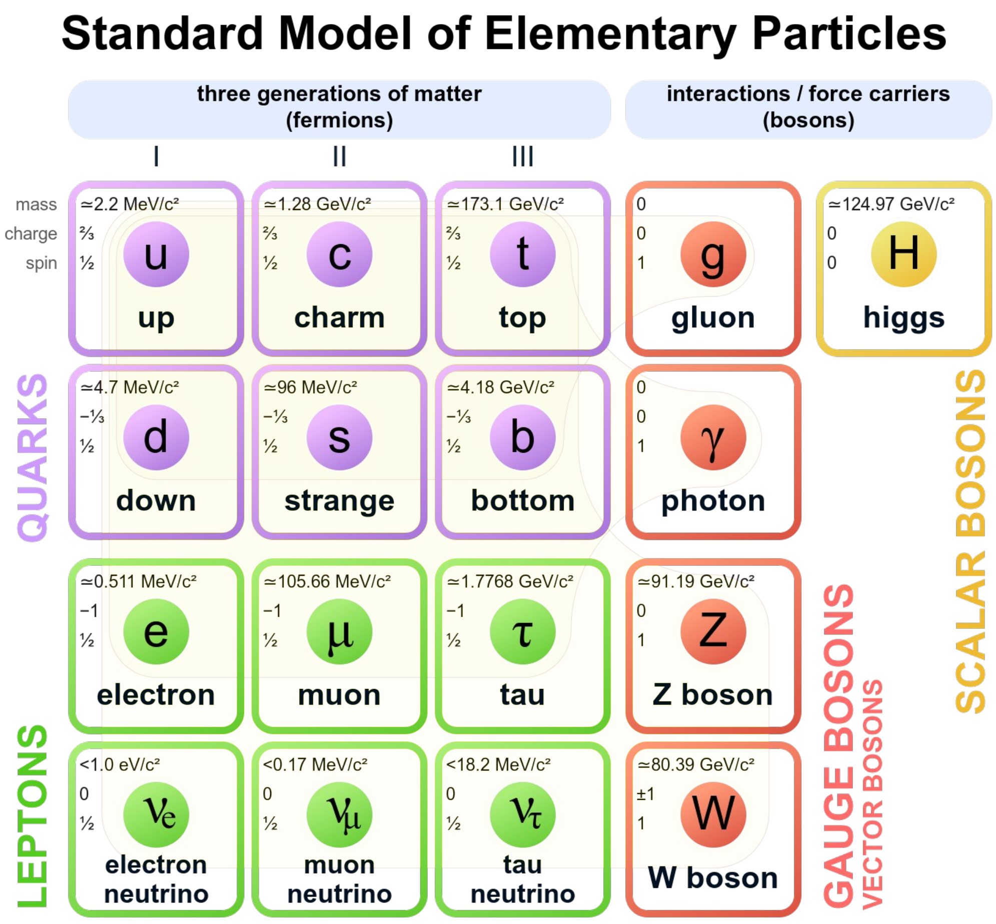
- **The Standard Model**
  - Theoretical problems of the Standard Model
  - Phenomenological problems of the Standard Model

- **Results from arXiv:2209.07971**

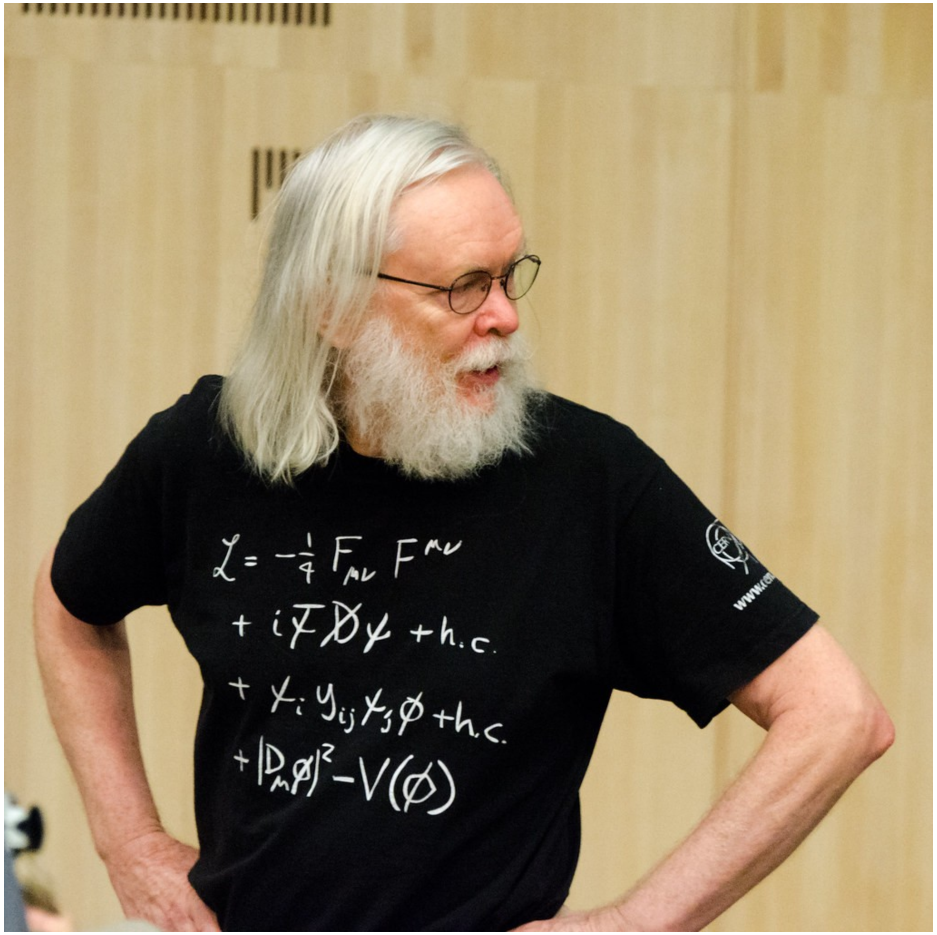
- **Type-II next-to-2HDM**
  - Details on the model
  - The seesaw mechanism
  - Observable: Analytical and Numerical machinery
  - Preliminary results

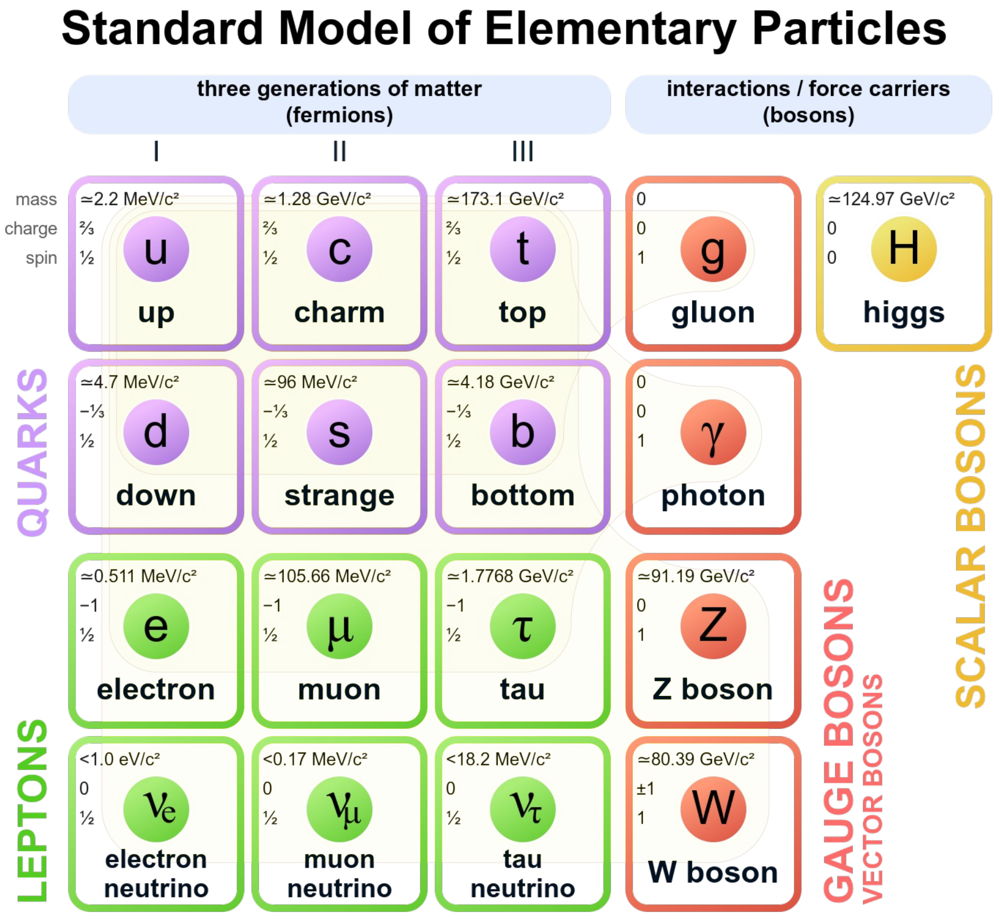
daniele.rizzo@ncbj.gov.pl
Daniele Rizzo

The Standard Model



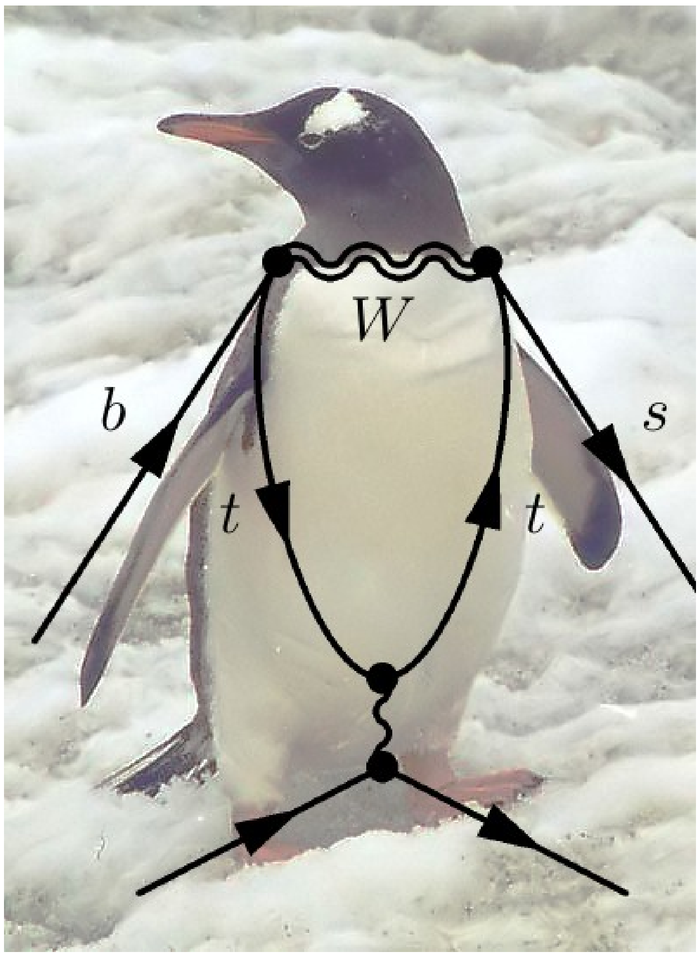
The Standard Model

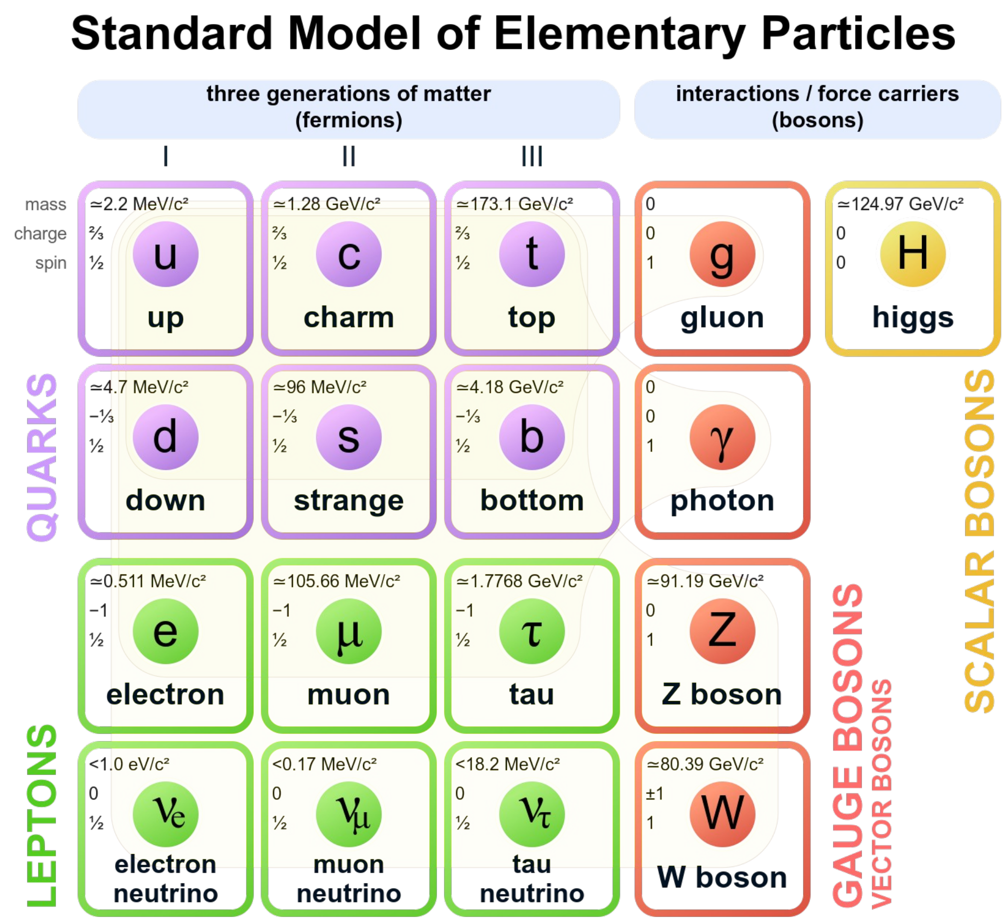




daniele.rizzo@ncbj.gov.pl
Daniele Rizzo

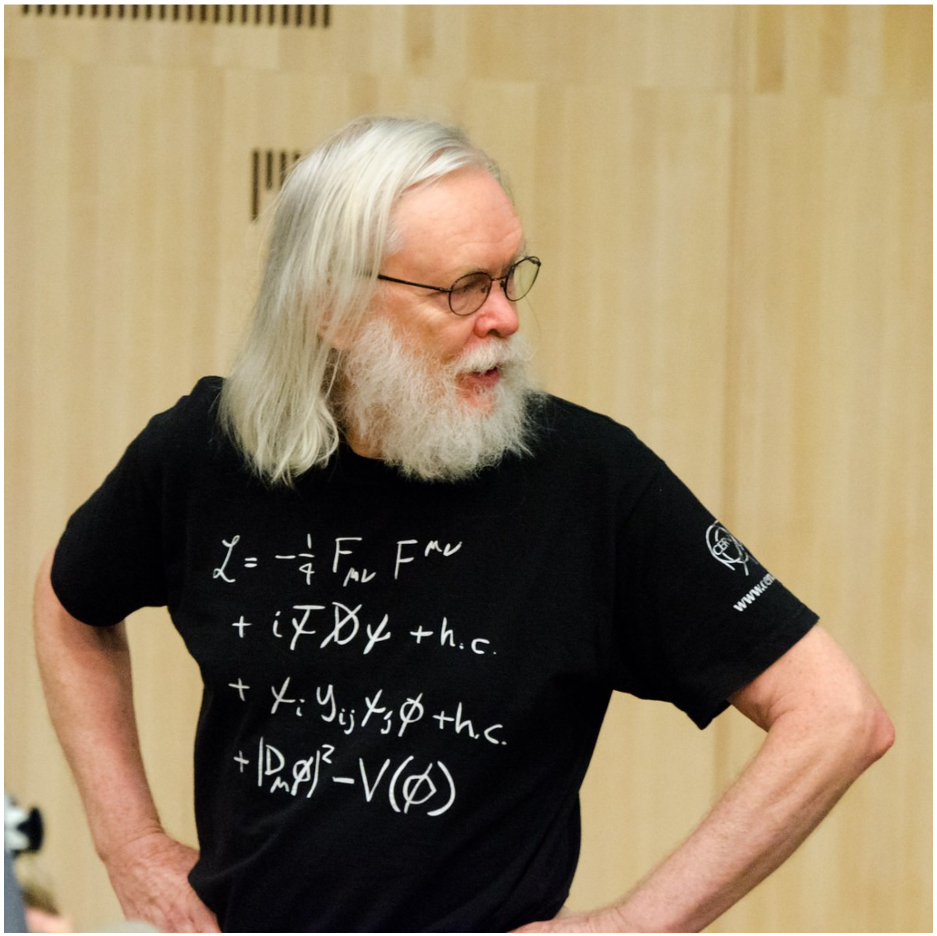
The Standard Model

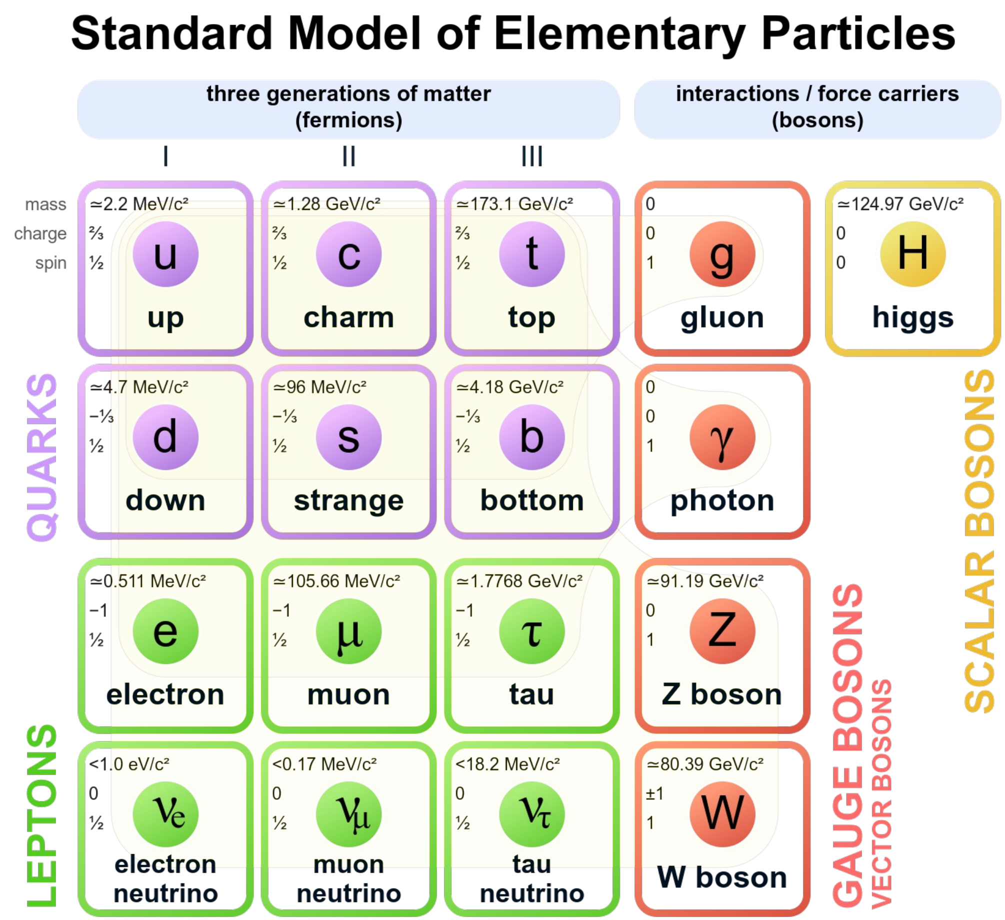




daniele.rizzo@ncbj.gov.pl
Daniele Rizzo

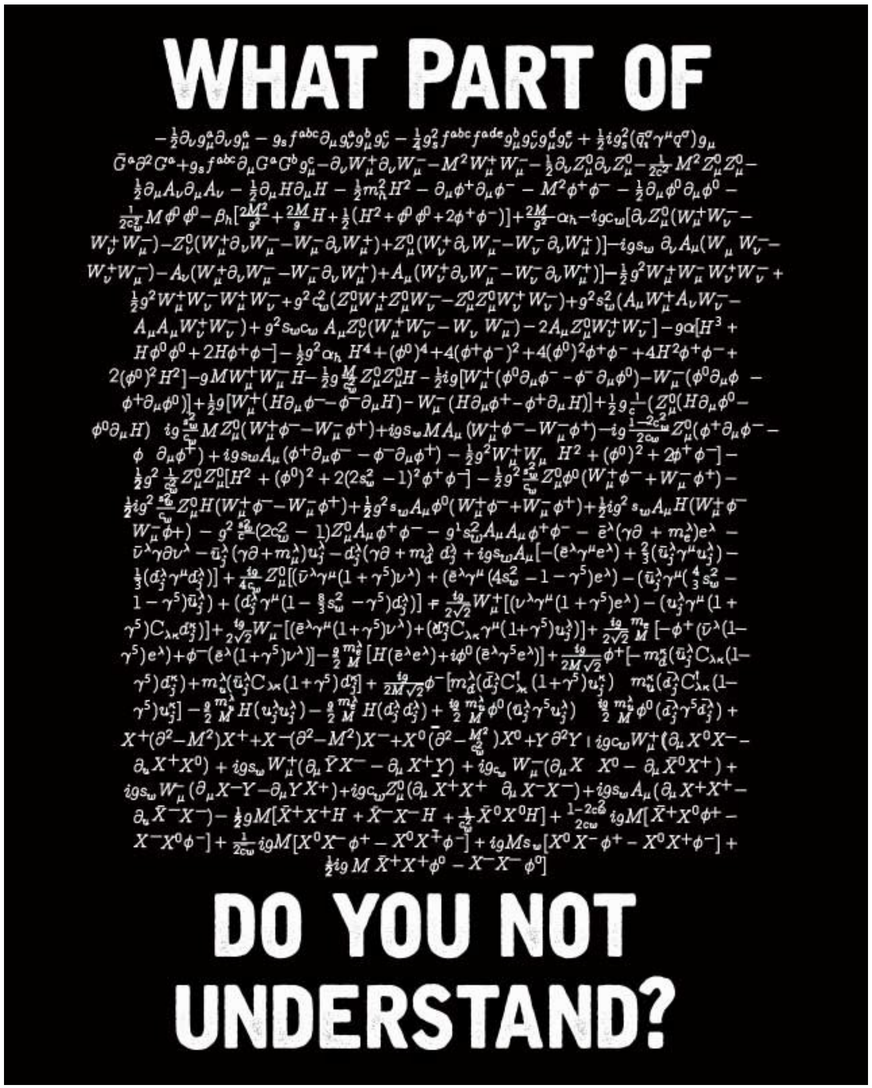
The Standard Model

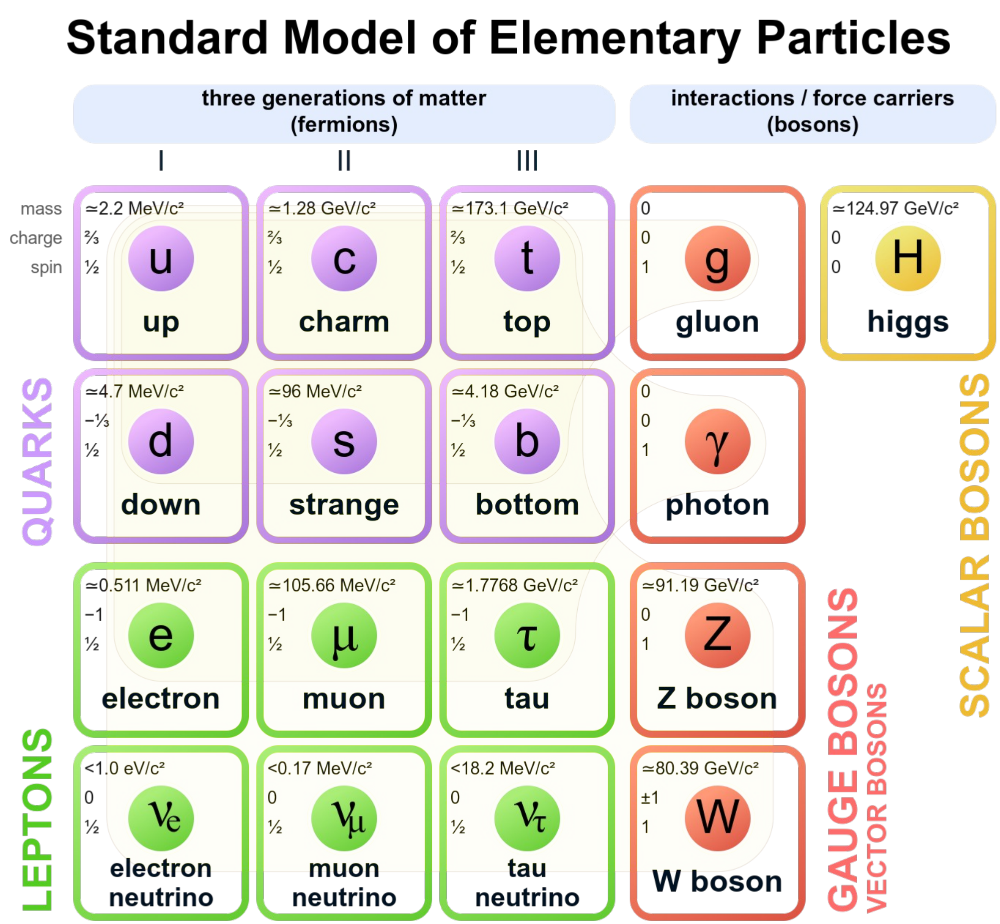




daniele.rizzo@ncbj.gov.pl
Daniele Rizzo

The Standard Model





daniele.rizzo@ncbj.gov.pl
Daniele Rizzo

The Standard Model

Gauge Bosons

$SU(3) \times SU(2)_L \times U(1)_Y$

Interactions

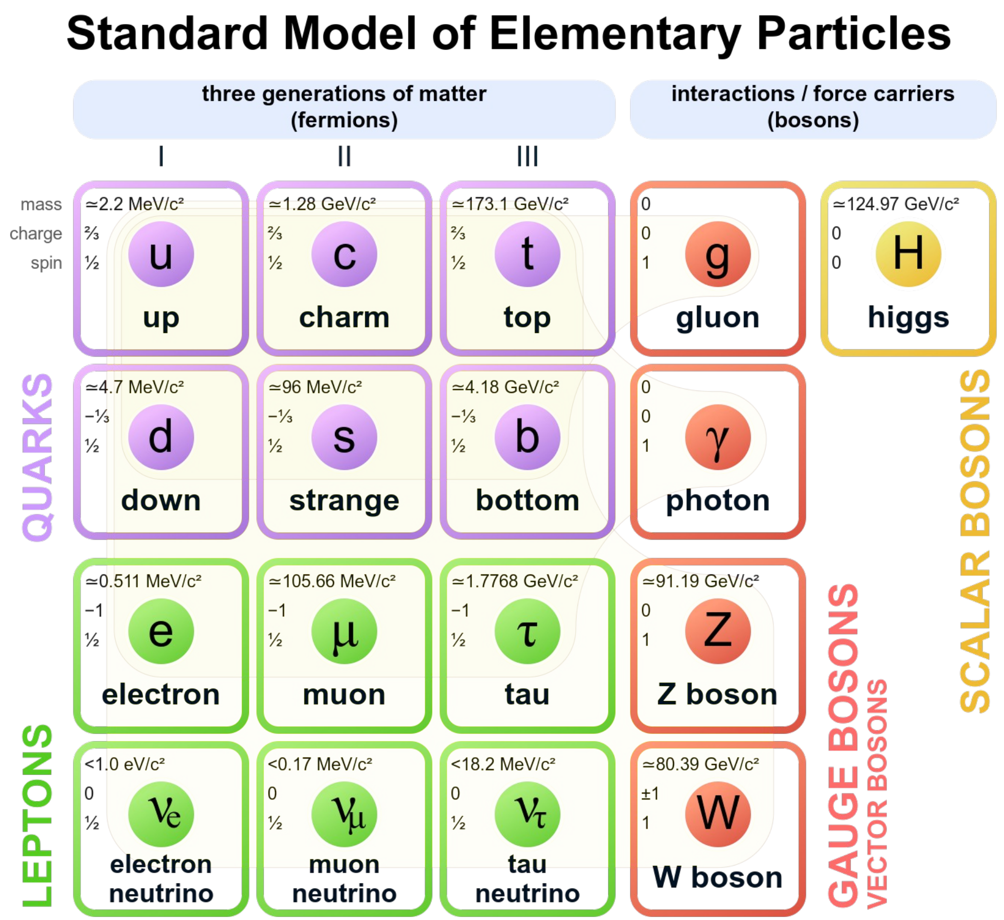
Strong

Electromagnetic

Flavor conserving neutral

Flavor conserving charged

Three generations, why?



daniele.rizzo@ncbj.gov.pl
Daniele Rizzo

Theoretical problems of The Standard Model

- Gravity
- Mass generation
- Dark matter
- UV completion
- Hierarchy
- Naturalness
- Nature of Neutrinos

daniele.rizzo@ncbj.gov.pl
Daniele Rizzo

The Standard Model

Mass generation

Dirac spinor in chiral representation

$$\psi_D = \begin{pmatrix} \psi_L \\ \psi_R \end{pmatrix}$$

Lagrangian of a Dirac spinor

$$\mathcal{L} = \bar{\psi}(i\partial\!\!\!/ - m)\psi$$

Vectorial

Axial

U(1) Transformation

$$\psi_D \to \mathrm{e}^{i\,\alpha}\psi_D$$

$$\psi_D \to \mathrm{e}^{i\,\gamma_5\,\beta}\psi_D$$

daniele.rizzo@ncbj.gov.pl

Daniele Rizzo

The Standard Model

Mass generation

Dirac spinor in chiral representation

$$\psi_D = \begin{pmatrix} \psi_L \\ \psi_R \end{pmatrix}$$

Lagrangian of a Dirac spinor

$$\mathcal{L} = \bar{\psi}(i\partial\!\!\!/ - m)\psi$$

Vectorial | Axial

U(1) Transformation

$$\psi_D \rightarrow \mathrm{e}^{i\,\alpha}\psi_D \qquad \psi_D \rightarrow \mathrm{e}^{i\,\gamma_5\,\beta}\psi_D$$

Noether conserved current (massless particle)

$$J_V^\mu = \bar{\psi}\gamma^\mu\psi \qquad J_A^\mu = \bar{\psi}\gamma^\mu\gamma_5\psi$$

daniele.rizzo@ncbj.gov.pl
Daniele Rizzo

The Standard Model

Mass generation

Dirac spinor in chiral representation

$$\psi_D = \begin{pmatrix} \psi_L \\ \psi_R \end{pmatrix}$$

Lagrangian of a Dirac spinor

$$\mathcal{L} = \bar{\psi}(i\partial\!\!\!/ - m)\psi$$

Vectorial | Axial

U(1) Transformation

$$\psi_D \to \mathrm{e}^{i\,\alpha}\psi_D \qquad \psi_D \to \mathrm{e}^{i\,\gamma_5\,\beta}\psi_D$$

Noether conserved current (massless particle)

$$J_V^\mu = \bar{\psi}\gamma^\mu\psi \qquad J_A^\mu = \bar{\psi}\gamma^\mu\gamma_5\psi$$

Massive particle

$$\partial_\mu J_V^\mu = 0 \qquad \partial_\mu J_A^\mu = 2i\,m\,(\bar{\psi}\gamma_5\psi)$$

daniele.rizzo@ncbj.gov.pl
Daniele Rizzo

The Standard Model

Mass generation

Dirac spinor in chiral representation

$$\psi_D = \begin{pmatrix} \psi_L \\ \psi_R \end{pmatrix}$$

Lagrangian of a Dirac spinor

$$\mathcal{L} = \bar{\psi}(i\partial\!\!\!/ - m)\psi$$

Vectorial | Axial

U(1) Transformation

$$\psi_D \to \mathrm{e}^{i\,\alpha}\psi_D \qquad \psi_D \to \mathrm{e}^{i\,\gamma_5\,\beta}\psi_D$$

Noether conserved current (massless particle)

$$J^\mu_V = \bar{\psi}\gamma^\mu\psi \qquad J^\mu_A = \bar{\psi}\gamma^\mu\gamma_5\psi$$

Massive particle

$$\partial_\mu J^\mu_V = 0 \qquad \partial_\mu J^\mu_A = 2i\,m\,(\bar{\psi}\gamma_5\psi)$$

$$\downarrow$$

$$m = 0$$

daniele.rizzo@ncbj.gov.pl

Daniele Rizzo

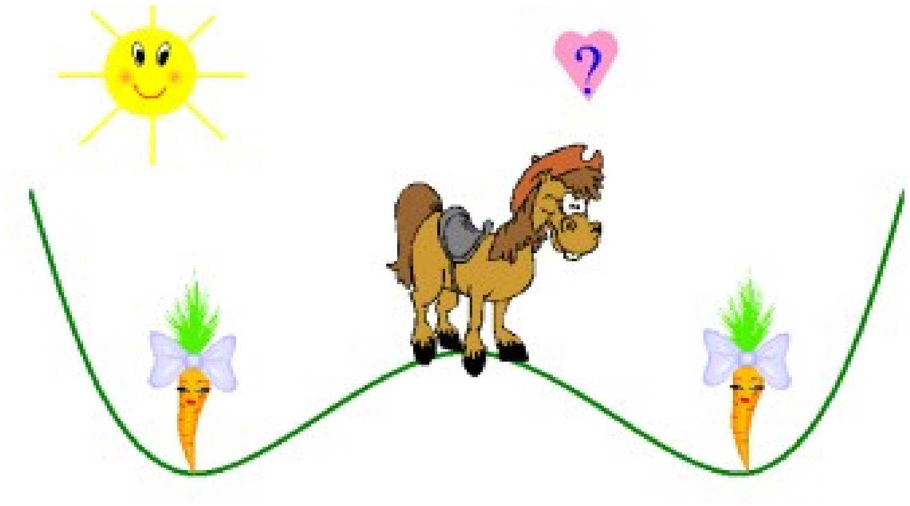
The Standard Model

Mass generation

daniele.rizzo@ncbj.gov.pl
Daniele Rizzo

The Standard Model

Mass generation

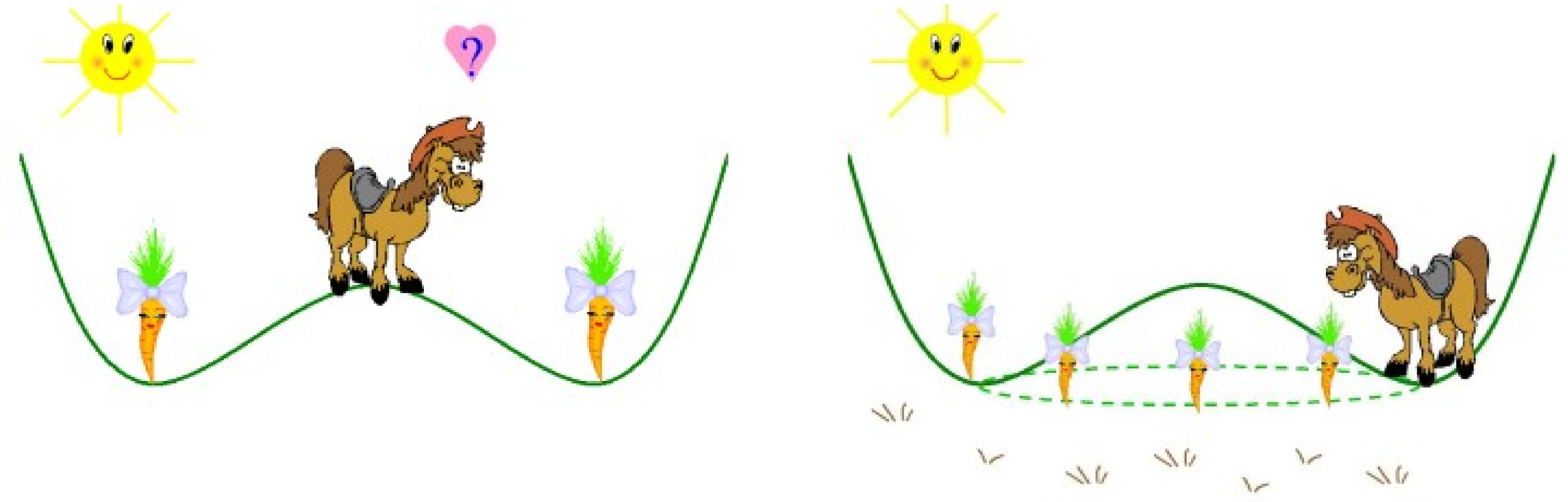


daniele.rizzo@ncbj.gov.pl

Daniele Rizzo

The Standard Model

Mass generation



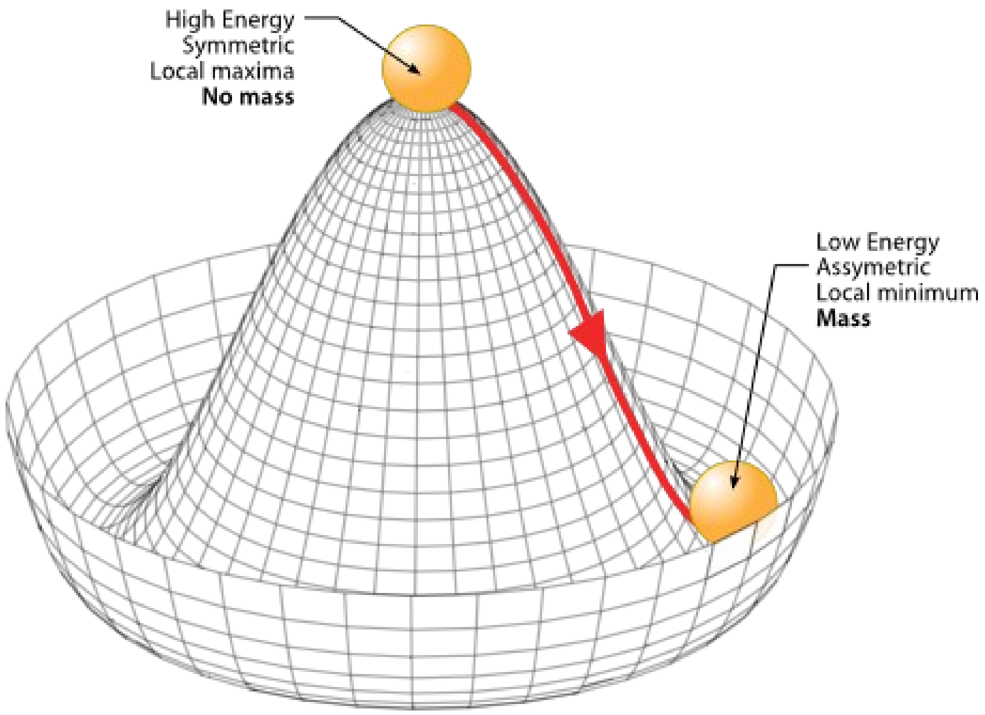
daniele.rizzo@ncbj.gov.pl

Daniele Rizzo

The Standard Model

Mass generation

$$\mathcal{L} = T - V$$



daniele.rizzo@ncbj.gov.pl
Daniele Rizzo

The Standard Model

Mass generation

$$\mathcal{L} = T - V = \frac{1}{2}\left(\partial_\mu \phi\right)^2 - \left(\frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4\right)$$

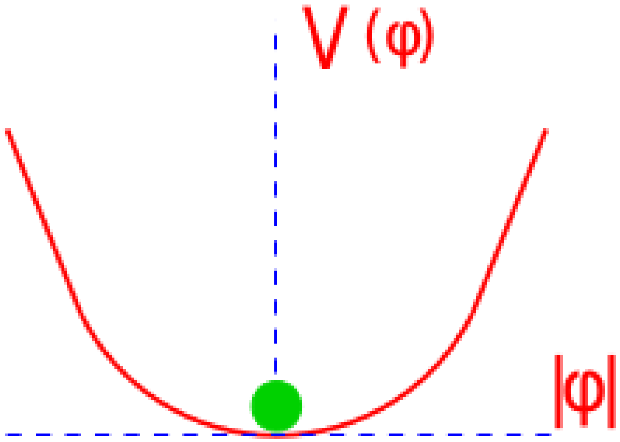
daniele.rizzo@ncbj.gov.pl
Daniele Rizzo

The Standard Model

Mass generation

$$\mathcal{L} = T - V = \frac{1}{2}\left(\partial_\mu \phi\right)^2 - \left(\frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4\right)$$

$$\mu^2 > 0$$



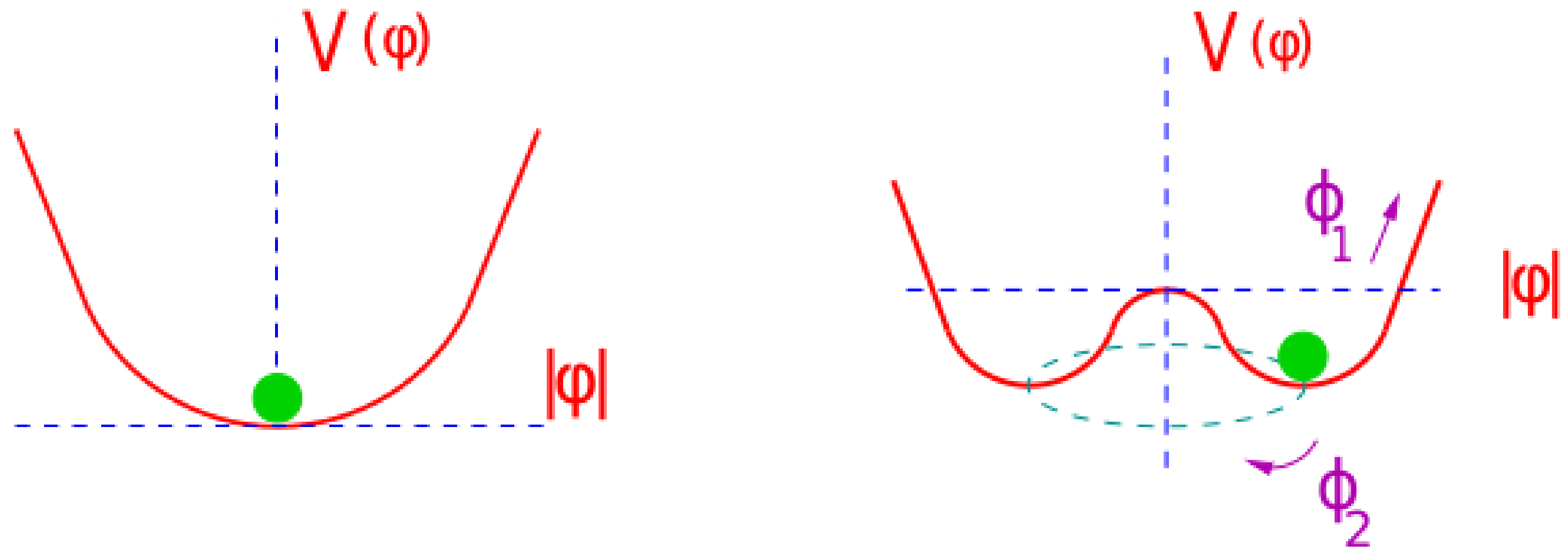
daniele.rizzo@ncbj.gov.pl
Daniele Rizzo

The Standard Model

Mass generation

$$\mathcal{L} = T - V = \frac{1}{2}\left(\partial_\mu \phi\right)^2 - \left(\frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4\right)$$

$\mu^2 > 0$ $\mu^2 < 0$



daniele.rizzo@ncbj.gov.pl

Daniele Rizzo

The Standard Model

Mass generation

$$\phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix}$$

$$\mathcal{L}_Y = \left\{ (\bar{q}'_u, \bar{q}'_d)_L \left[c^{(d)} \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} (q'_d)_R + c^{(u)} \begin{pmatrix} \phi^{0\dagger} \\ \phi^{+\dagger} \end{pmatrix} (q_u)'_R \right] + (\bar{\nu}'_r, \bar{l}'_r)_L c^{(l)} \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} l'_R + h.c \right\}$$

$$\mathcal{L}_Y = -\left(1 + \frac{H}{v}\right) \left\{ \bar{d}\mathcal{M}_d d + \bar{u}\mathcal{M}_u u + \bar{l}\mathcal{M}_l l + h.c \right\}$$

daniele.rizzo@ncbj.gov.pl

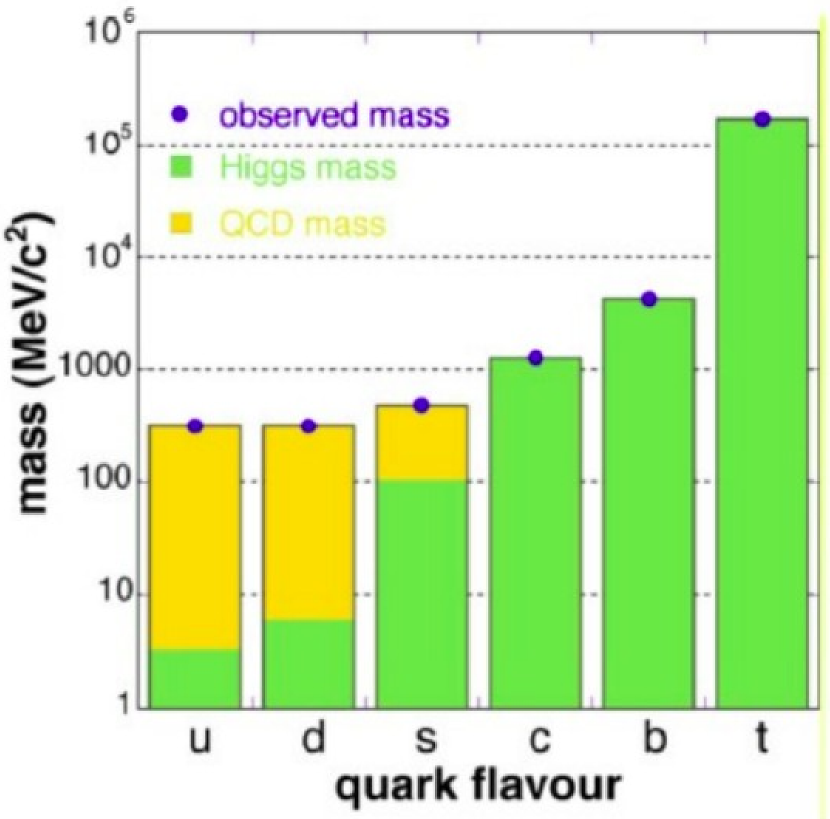
Daniele Rizzo

Theoretical problems of The Standard Model

Mass generation

Mass Proton = 1GeV

Mass up+up+down= 9.1MeV



daniele.rizzo@ncbj.gov.pl

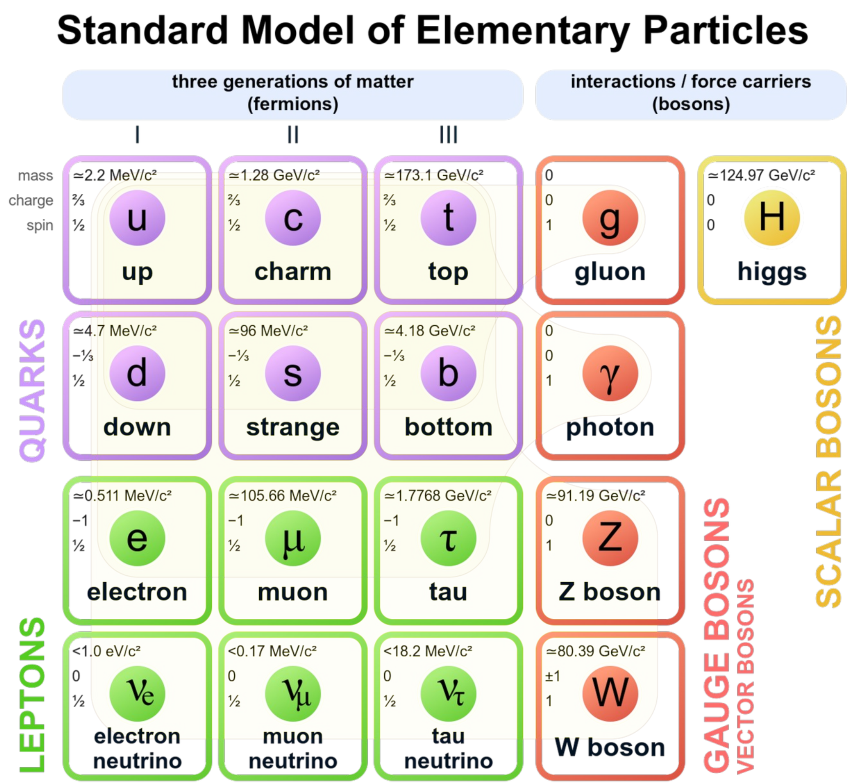
Daniele Rizzo

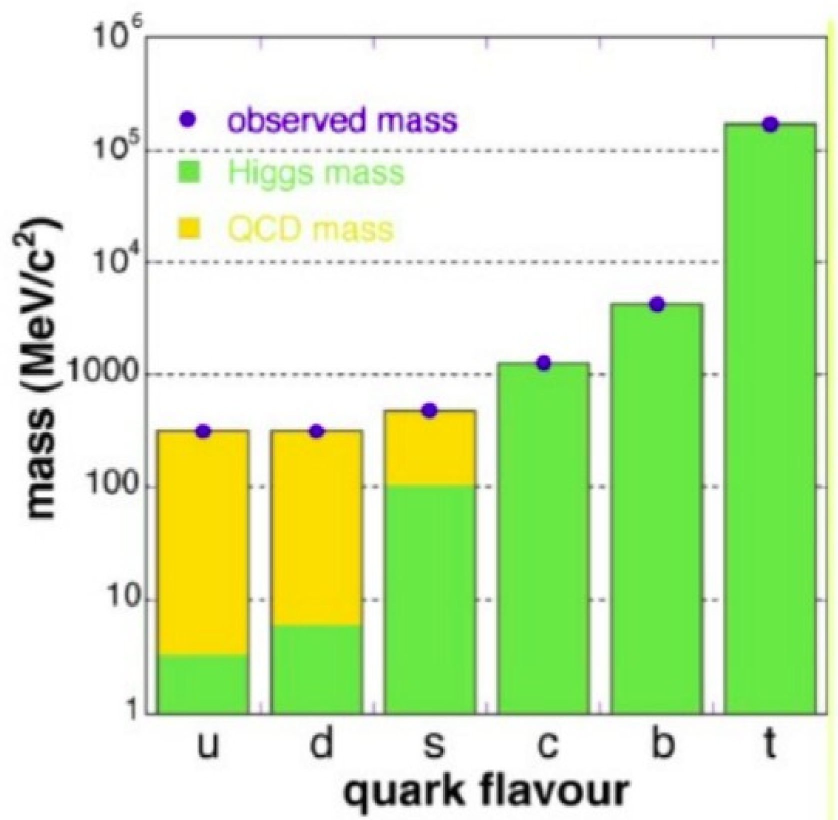
Theoretical problems of The Standard Model

Mass generation

Mass Proton = 1GeV

Mass up+up+down= 9.1MeV





daniele.rizzo@ncbj.gov.pl

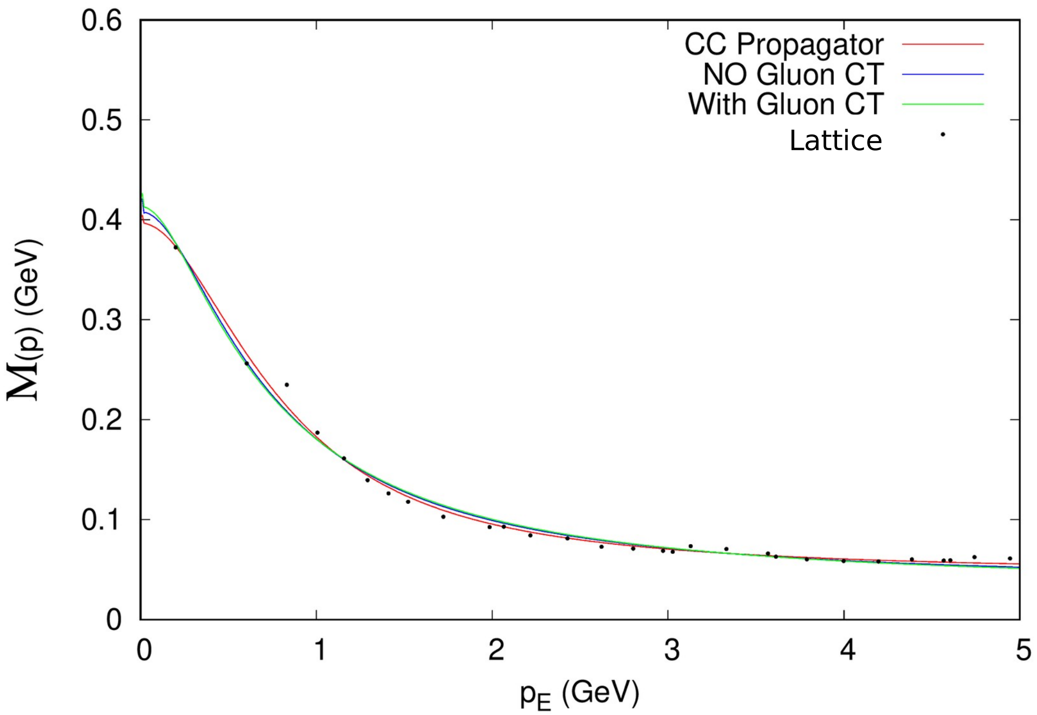
Daniele Rizzo

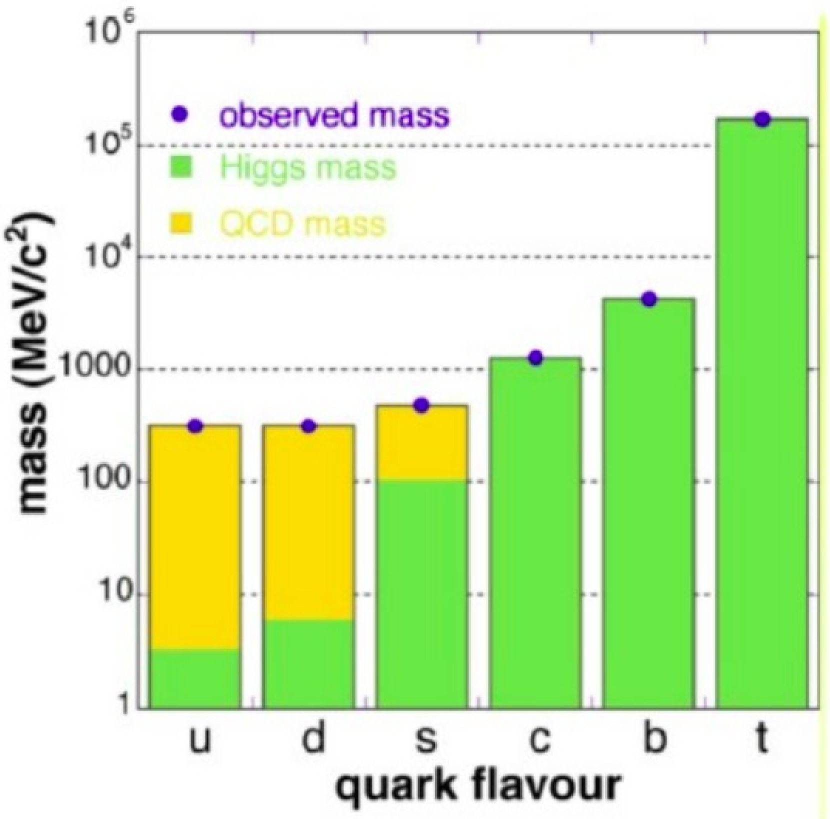
Theoretical problems of The Standard Model

Mass generation

Mass Proton = 1GeV

Mass up+up+down= 9.1MeV





G. Comitini, **DR** *et al*, PRD 104, 074020.

Phenomenological problems of The Standard Model

Muonic (g-2)

Flavor Conserving Neutral Currents

Flavor Conserving Charged Currents

W mass anomaly

daniele.rizzo@ncbj.gov.pl

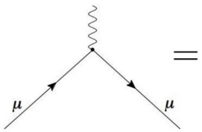
Daniele Rizzo

Phenomenological problems of The Standard Model

Muonic (g-2)

The magnetic moment of charged leptons (e, μ, τ): $\vec{\mu} = g\frac{e}{2m}\vec{S}$

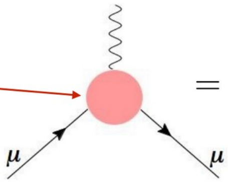
Dirac (leading order): $g = 2$



$$= (-ie)\,\bar{u}(p')\gamma^\mu u(p)$$

Quantum effects (loops):

All SM particles contribute

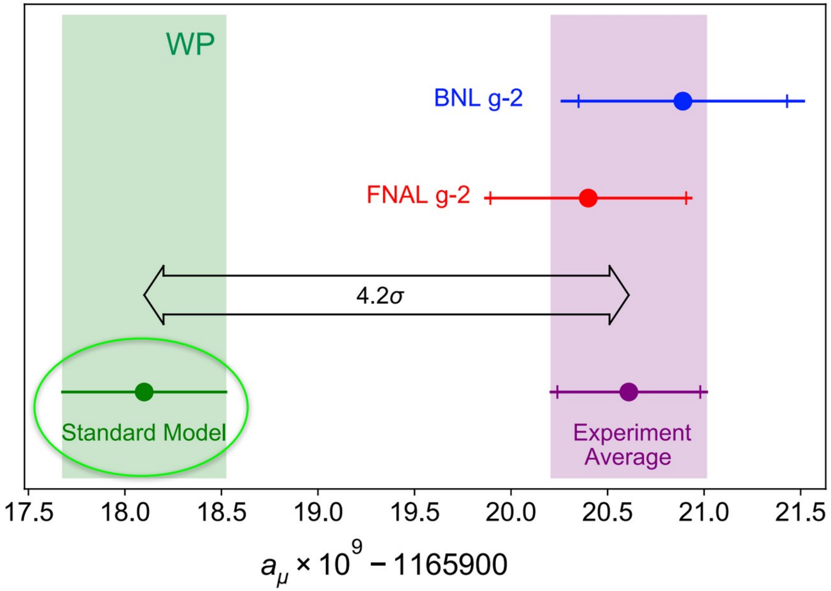


$$= (-i\,e)\,\bar{u}(p')\left[\gamma^\mu F_1(q^2) + \frac{i\sigma^{\mu\nu}q_\nu}{2m}F_2(q^2)\right]u(p)$$

Note: $F_1(0) = 1$ and $g = 2 + 2\,F_2(0)$

Anomalous magnetic moment: $a \equiv \frac{g-2}{2} = F_2(0)$

$$\Delta a_\mu = a_\mu^{\mathrm{Exp}} - a_\mu^{\mathrm{SM}} = (26.1 \pm 8.0) \times 10^{-10}$$
$$\Delta a_e = a_e^{\mathrm{Exp}} - a_e^{\mathrm{SM}} = (-0.88 \pm 0.36) \times 10^{-12}$$

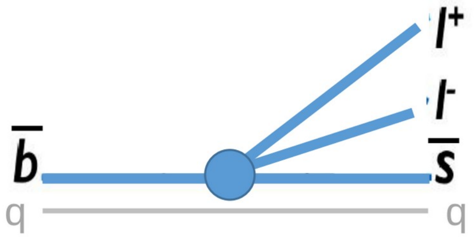


The status of muon g-2 theory: Aida El-Khadra
Higgs, Flavor and Beyond – DESY Theory Workshop

daniele.rizzo@ncbj.gov.pl
Daniele Rizzo

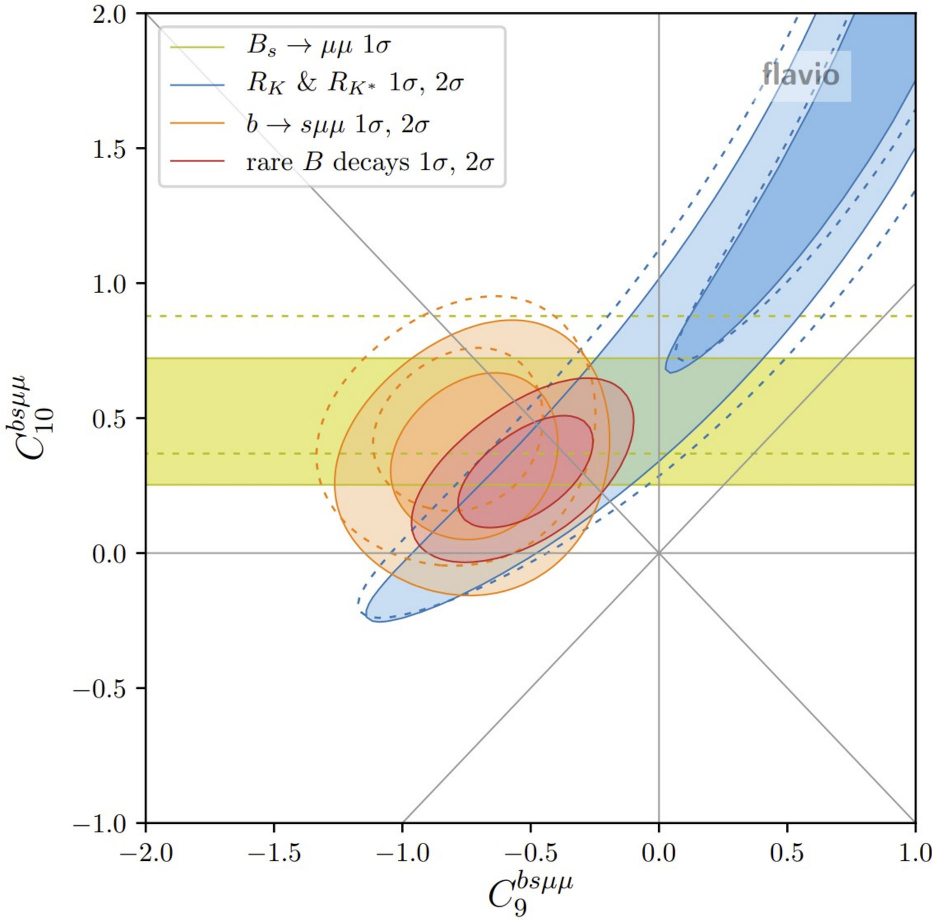
Phenomenological problems of The Standard Model

Flavor Conserving Neutral Currents



$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}} V_{tb} V_{tx}^* \sum_i C_i O_i$$

$$C_i = C_i^{SM} + C_i^{NP}$$



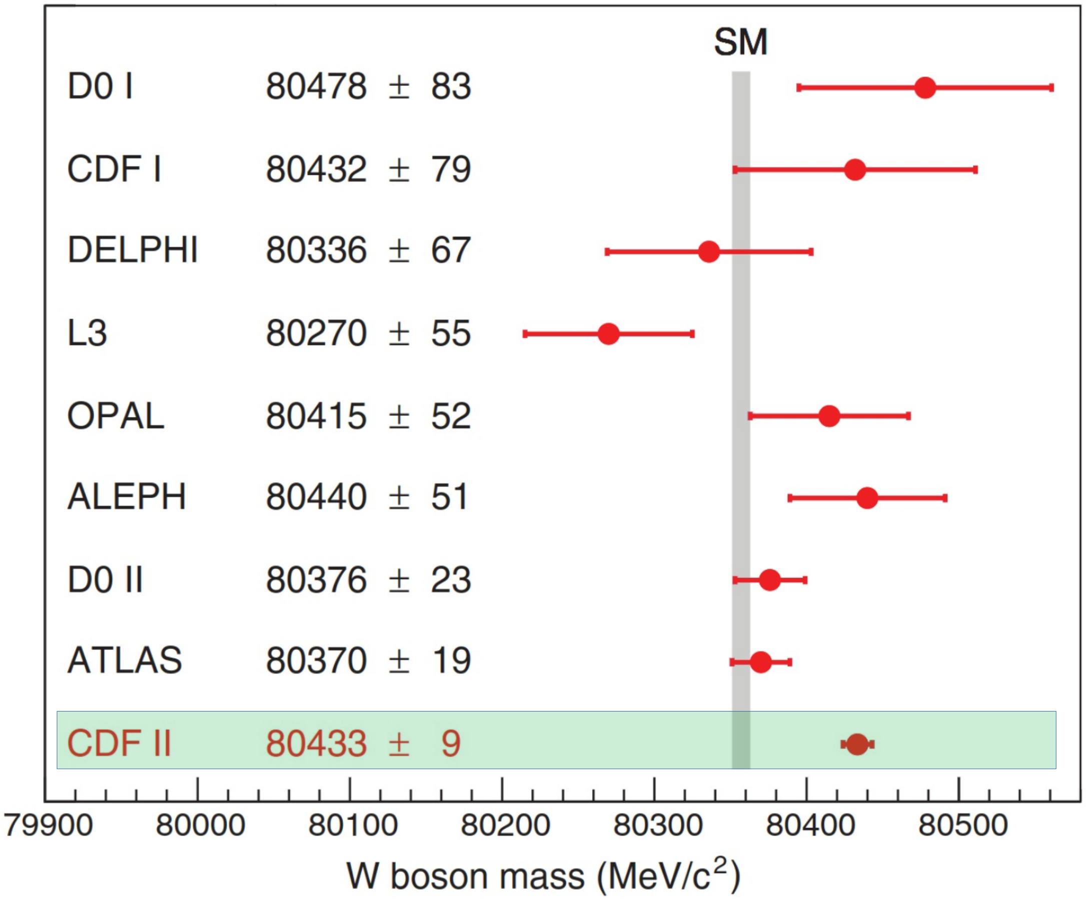
daniele.rizzo@ncbj.gov.pl
Daniele Rizzo

Phenomenological problems of The Standard Model

W mass anomaly

Table 2. Uncertainties on the combined M_W result.

Source	Uncertainty (MeV)
Lepton energy scale	3.0
Lepton energy resolution	1.2
Recoil energy scale	1.2
Recoil energy resolution	1.8
Lepton efficiency	0.4
Lepton removal	1.2
Backgrounds	3.3
p_T^Z model	1.8
p_T^W/p_T^Z model	1.3
Parton distributions	3.9
QED radiation	2.7
W boson statistics	6.4
Total	9.4



CDF Collaboration, doi:10.1126/science.abk1781

daniele.rizzo@ncbj.gov.pl
Daniele Rizzo

Phenomenological problems of The Standard Model

W mass anomaly

$$0.0496 < \Delta M_W < 0.0624$$ (GeV)

$$\Delta M_W = M_W^{\exp} - M_W^{\mathrm{SM}} \approx \frac{\alpha_{\mathrm{EM}}(M_Z)\cos^2\theta_W M_Z^2}{2M_W^{\mathrm{SM}}\left(\cos^2\theta_W - \sin^2\theta_W\right)}\left[-\frac{\Delta S}{2} + \cos^2\theta_W \Delta T + \frac{\cos^2\theta_W - \sin^2\theta_W}{4\sin^2\theta_W}\Delta U\right]$$

$$S = \frac{2\sin 2\theta_W}{\alpha_{\mathrm{EM}}(M_Z)} \frac{d\Pi_{30}(q^2)}{dq^2}\bigg|_{q^2=0},$$

$$\Delta S = 0.06 \pm 0.10.$$

$$T = \frac{\Pi_{33}(q^2) - \Pi_{11}(q^2)}{\alpha_{\mathrm{EM}}(M_Z) M_W^2}\bigg|_{q^2=0},$$

$$\Delta T = 0.11 \pm 0.12.$$

$$U = \frac{4\sin^2\theta_W}{\alpha_{\mathrm{EM}}(M_Z)}\left(\frac{d\Pi_{33}(q^2)}{dq^2} - \frac{d\Pi_{11}(q^2)}{dq^2}\right)\bigg|_{q^2=0},$$

$$\Delta U = 0.13 \pm 0.09$$

daniele.rizzo@ncbj.gov.pl

Daniele Rizzo

Outline

- **The Standard Model**
  - Theoretical problems of the Standard Model
  - Phenomenological problems of the Standard Model
- **Results from arXiv:2209.07971**
- **Type-II next-to-2HDM**
  - Details on the model
  - The seesaw mechanism
  - Observable: Analytical and Numerical machinery
  - Preliminary results

Outline

- **The Standard Model**
  - Theoretical problems of the Standard Model
  - Phenomenological problems of the Standard Model

- **Results from arXiv:2209.07971**

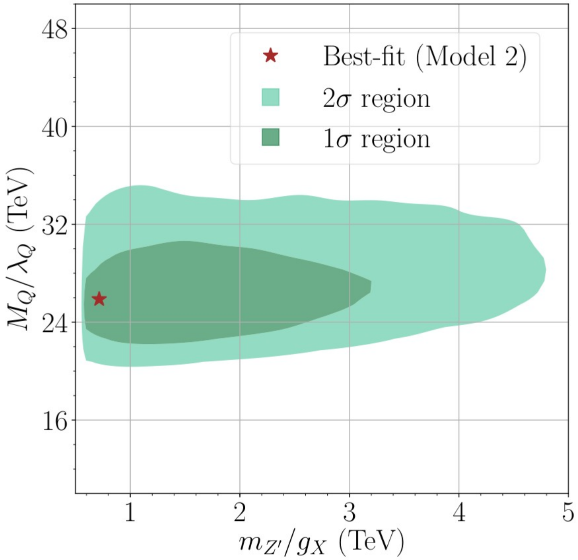
- **Type-II next-to-2HDM**
  - Details on the model
  - The seesaw mechanism
  - Observable: Analytical and Numerical machinery
  - Preliminary results

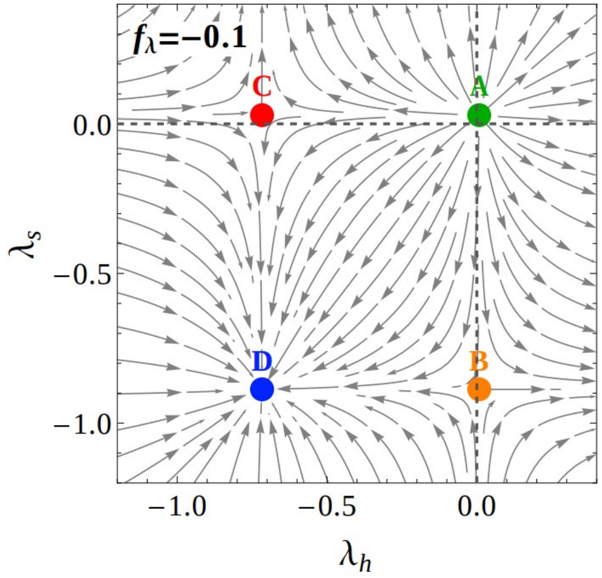
Results from arXiv:2209.07971

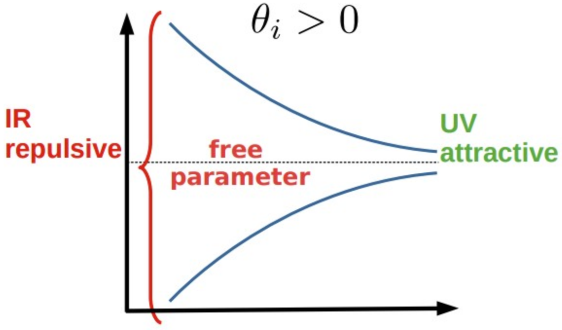
8 free parameters → Less predictive

$$\beta_g = \beta_g^{\mathrm{SM+NP}} - g\, f_g,$$
$$\beta_y = \beta_y^{\mathrm{SM+NP}} - y\, f_y,$$
$$\beta_\lambda = \beta_\lambda^{\mathrm{SM+NP}} - \lambda\, f_\lambda,$$

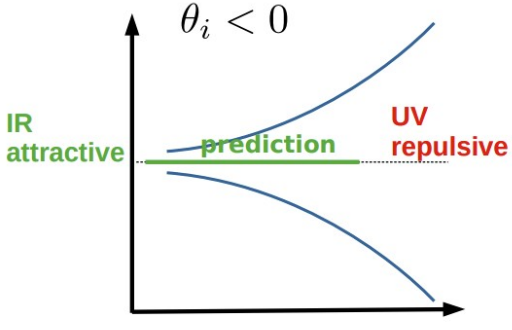
$$Q : (\mathbf{3}, \mathbf{2}, 1/6, Q_S)$$
$$L : (\mathbf{1}, \mathbf{2}, -1/2, Q_L)$$
$$S : (\mathbf{1}, \mathbf{1}, 0, Q_S)$$







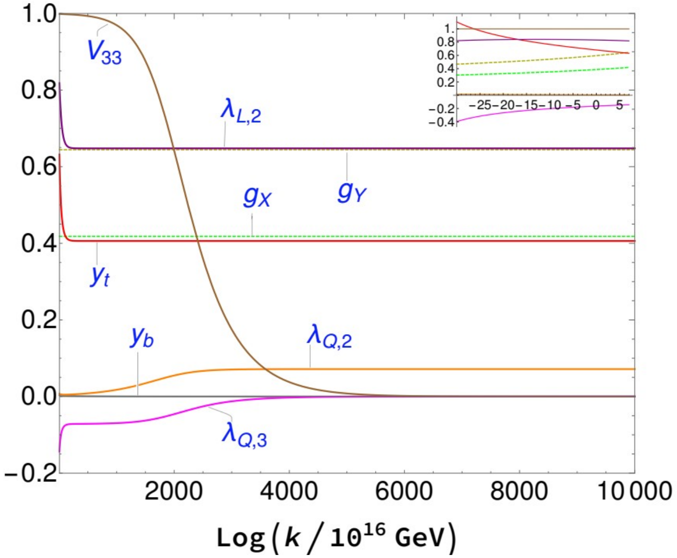
Relevant couplings are free parameters of the theory



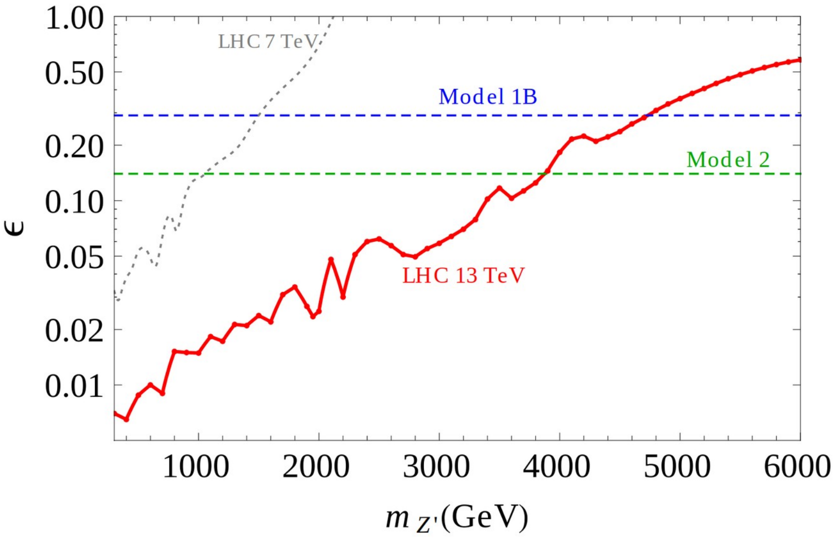
Irrelevant couplings provide predictions

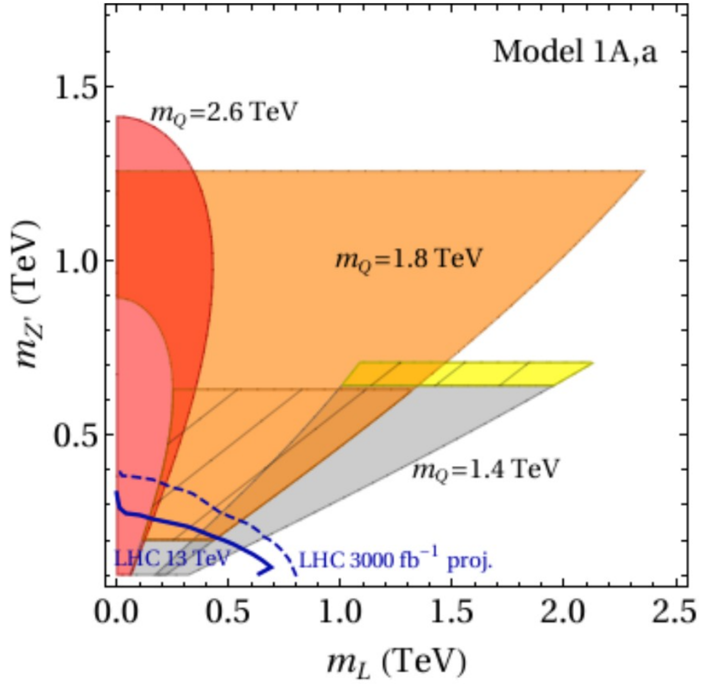
daniele.rizzo@ncbj.gov.pl
Daniele Rizzo

Results from arXiv:2209.07971



	$g_Y(k_0)$	$g_D(k_0)$	$g_\epsilon(k_0)$	$y_t(k_0)$	$\lambda_{Q,3}(k_0)$	$\lambda_{Q,2}(k_0)$	$\lambda_{L,2}(k_0)$
$FP_{1A,a}$	0.364	0.305	0	1.08	-0.381	0.016	0.823
$FP_{1A,b}$	0.364	0.305	0	1.09	0.034	0.803	0.606
$FP_{1B,a}$	0.363	0.318	0.110	1.05	-0.612	0.296	0.652
$FP_{1B,b}$	0.363	0.318	0.110	1.08	0.004	0.874	0.499
$FP_{2,a}$	0.363	0.277	0.052	1.03	-0.700	0.638	–
$FP_{2,b}$	0.363	0.277	0.052	1.10	0.040	0.988	–





daniele.rizzo@ncbj.gov.pl

Daniele Rizzo

Outline

- **The Standard Model**
  - Theoretical problems of the Standard Model
  - Phenomenological problems of the Standard Model

- **Results from arXiv:2209.07971**

- **Type-II next-to-2HDM**
  - Details on the model
  - The seesaw mechanism
  - Observable: Analytical and Numerical machinery
  - Preliminary results

daniele.rizzo@ncbj.gov.pl Daniele Rizzo

Local vs Global Symmetries in QFT

daniele.rizzo@ncbj.gov.pl
Daniele Rizzo

Local vs Global Symmetries in QFT

Hamiltonian of the Ising model

$$H = J \sum_{<ij>} \sigma_i \sigma_j - h \sum_{i=1}^{N} \sigma_i$$

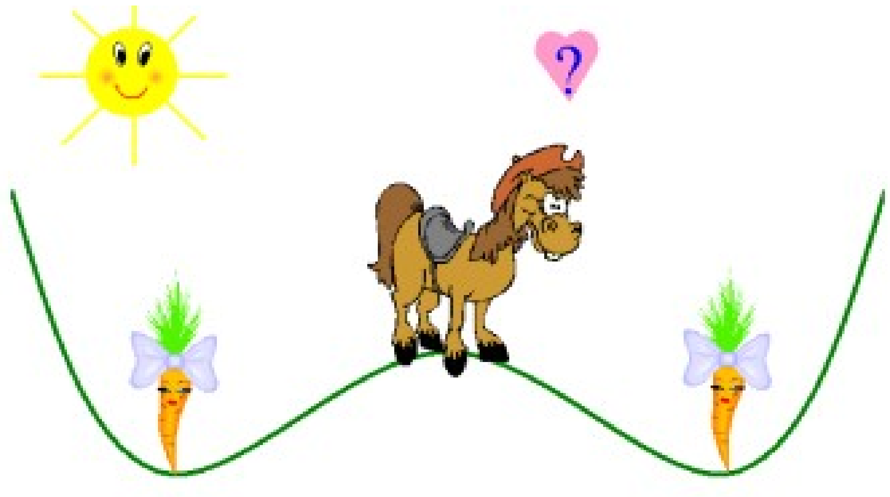
daniele.rizzo@ncbj.gov.pl

Daniele Rizzo

Local vs Global Symmetries in QFT

Hamiltonian of the Ising model

$$H = J \sum_{<ij>} \sigma_i \sigma_j - h \sum_{i=1}^{N} \sigma_i$$



daniele.rizzo@ncbj.gov.pl

Daniele Rizzo

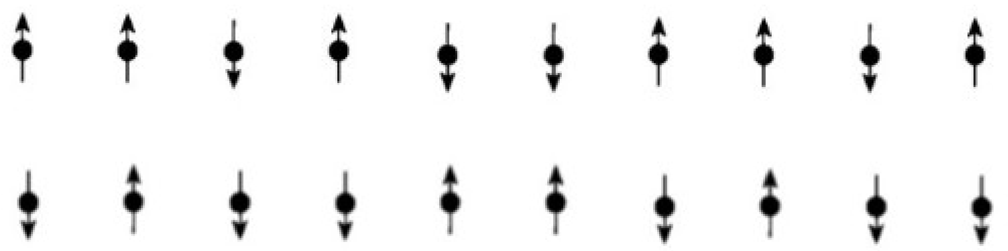
Local vs Global Symmetries in QFT

Hamiltonian of the Ising model

$$H = J \sum_{<ij>} \sigma_i \sigma_j - h \sum_{i=1}^{N} \sigma_i$$

Generic configuration

All spin flipped



Same energy

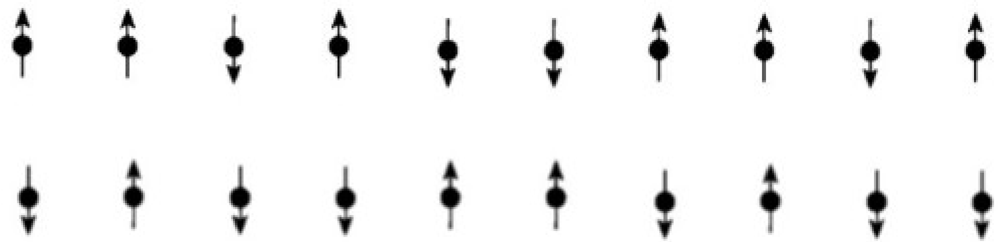
Local vs Global Symmetries in QFT

Hamiltonian of the Ising model

$$H = J \sum_{<ij>} \sigma_i \sigma_j - h \sum_{i=1}^{N} \sigma_i$$

Generic configuration

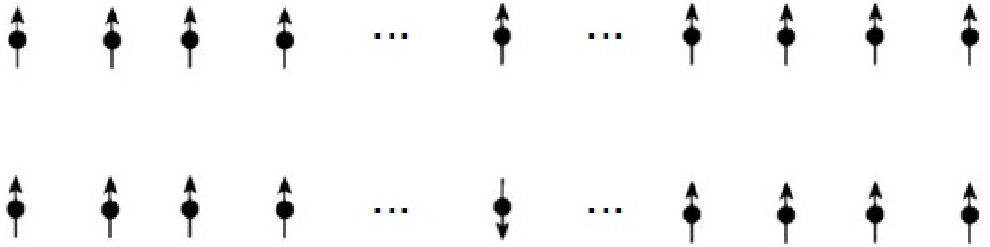
All spin flipped



Same energy

Generic configuration

Only one spin flipped



Different energy

daniele.rizzo@ncbj.gov.pl

Daniele Rizzo

Local vs Global Symmetries in QFT

Global Transformation ← U(1) → Local Transformation

$$\psi(x) \to \mathrm{e}^{i\,q\,\theta}\psi(x)$$

$$\psi(x) \to \mathrm{e}^{i\,q\,\theta(x)}\psi(x)$$

daniele.rizzo@ncbj.gov.pl Daniele Rizzo

Local vs Global Symmetries in QFT

Global Transformation ← U(1) → Local Transformation

$$\psi(x) \rightarrow \mathrm{e}^{i\,q\,\theta}\psi(x)$$

$$\psi(x) \rightarrow \mathrm{e}^{i\,q\,\theta(x)}\psi(x)$$

$$\mathcal{L}_D = \psi(\bar{x})(i\gamma^\mu\partial_\mu - m)\psi(x)$$

daniele.rizzo@ncbj.gov.pl
Daniele Rizzo

Local vs Global Symmetries in QFT

Global Transformation ← U(1) → Local Transformation

$$\psi(x) \rightarrow \mathrm{e}^{i\,q\,\theta}\psi(x)$$

$$\psi(x) \rightarrow \mathrm{e}^{i\,q\,\theta(x)}\psi(x)$$

$$\mathcal{L}_D = \bar{\psi}(x)(i\gamma^\mu\partial_\mu - m)\psi(x) \rightarrow \mathcal{L}_D - q\bar{\psi}(x)(\gamma^\mu\partial_\mu\theta)\psi(x)$$

daniele.rizzo@ncbj.gov.pl
Daniele Rizzo

Local vs Global Symmetries in QFT

Global Transformation ← U(1) → Local Transformation

$$\psi(x) \to e^{i\,q\,\theta}\psi(x) \qquad\qquad \psi(x) \to e^{i\,q\,\theta(x)}\psi(x)$$

$$\mathcal{L}_D = \bar{\psi(x)}(i\gamma^\mu\partial_\mu - m)\psi(x) \to \mathcal{L}_D - q\bar{\psi(x)}(\gamma^\mu\partial_\mu\theta)\psi(x)$$

Covariant Derivative $\partial_\mu \to D_\mu = \partial_\mu + iqA_\mu(x)$

daniele.rizzo@ncbj.gov.pl Daniele Rizzo

Local vs Global Symmetries in QFT

Global Transformation ← U(1) → Local Transformation

$$\psi(x) \to e^{i\,q\,\theta}\psi(x) \qquad\qquad \psi(x) \to e^{i\,q\,\theta(x)}\psi(x)$$

$$\mathcal{L}_D = \bar{\psi(x)}(i\gamma^\mu\partial_\mu - m)\psi(x) \to \mathcal{L}_D - q\bar{\psi(x)}(\gamma^\mu\partial_\mu\theta)\psi(x)$$

Covariant Derivative $\partial_\mu \to D_\mu = \partial_\mu + iqA_\mu(x)$

Electromagnetic field

Conserved current $J^\mu_V = \bar{\psi}\gamma^\mu\psi$

daniele.rizzo@ncbj.gov.pl
Daniele Rizzo

Type-II next-to-2HDM

Field	Q_{iL}	u_{iR}	d_{iR}	L_{iL}	e_{iR}	Q_{kL}	u_{kR}	d_{kR}	L_{kL}	e_{kR}	ν_{kR}	$\widetilde{Q}_{kR}$	$\widetilde{u}_{kL}$	$\widetilde{d}_{kL}$	$\widetilde{L}_{kR}$	$\widetilde{e}_{kL}$	$\widetilde{\nu}_{kR}$	ϕ	H_u	H_d
$SU(3)_C$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$SU(2)_L$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{2}$
$U(1)_Y$	$\frac{1}{6}$	$\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{1}{2}$	1	$\frac{1}{6}$	$\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{1}{2}$	-1	0	$\frac{1}{6}$	$\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{1}{2}$	-1	0	0	$\frac{1}{2}$	$-\frac{1}{2}$
$U(1)'$	0	0	0	0	0	1	-1	-1	1	-1	-1	1	-1	-1	1	-1	-1	1	-1	-1

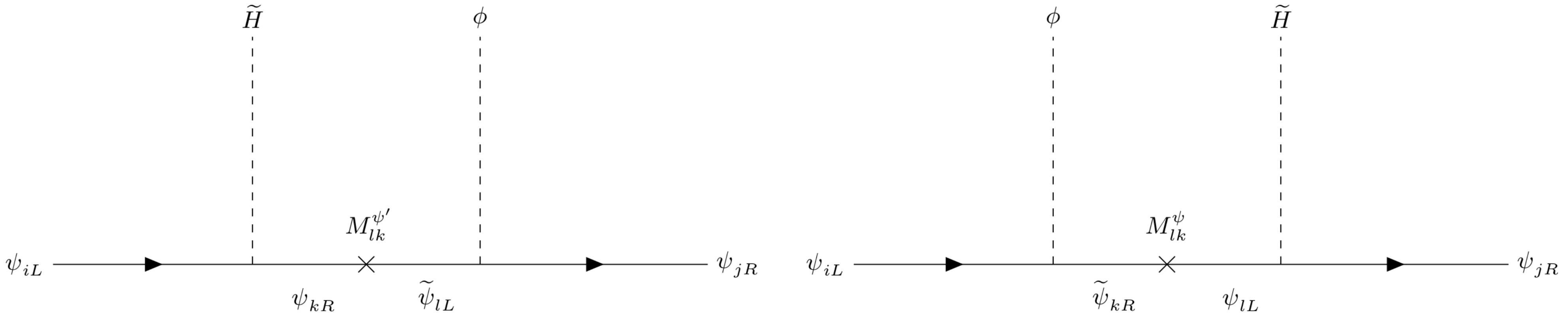


Figure 2: Diagrams in this model which lead to the effective Yukawa interactions, where $\psi, \psi' = Q, u, d, L, e$(neutrinos will be treated separately) $i, j = 1, 2, 3,\ k, l = 4,\ M_{lk}$ is vectorlike mass and $\widetilde{H} = i\sigma_2 H^*, H = H_{u,d}$

daniele.rizzo@ncbj.gov.pl
Daniele Rizzo

Type-II next-to-2HDM

Field	Q_{iL}	u_{iR}	d_{iR}	L_{iL}	e_{iR}	Q_{kL}	u_{kR}	d_{kR}	L_{kL}	e_{kR}	ν_{kR}	$\widetilde{Q}_{kR}$	$\widetilde{u}_{kL}$	$\widetilde{d}_{kL}$	$\widetilde{L}_{kR}$	$\widetilde{e}_{kL}$	$\widetilde{\nu}_{kR}$	ϕ	H_u	H_d
$SU(3)_C$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$SU(2)_L$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{2}$
$U(1)_Y$	$\frac{1}{6}$	$\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{1}{2}$	1	$\frac{1}{6}$	$\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{1}{2}$	-1	0	$\frac{1}{6}$	$\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{1}{2}$	-1	0	0	$\frac{1}{2}$	$-\frac{1}{2}$
$U(1)'$	0	0	0	0	0	1	-1	-1	1	-1	-1	1	-1	-1	1	-1	-1	1	-1	-1

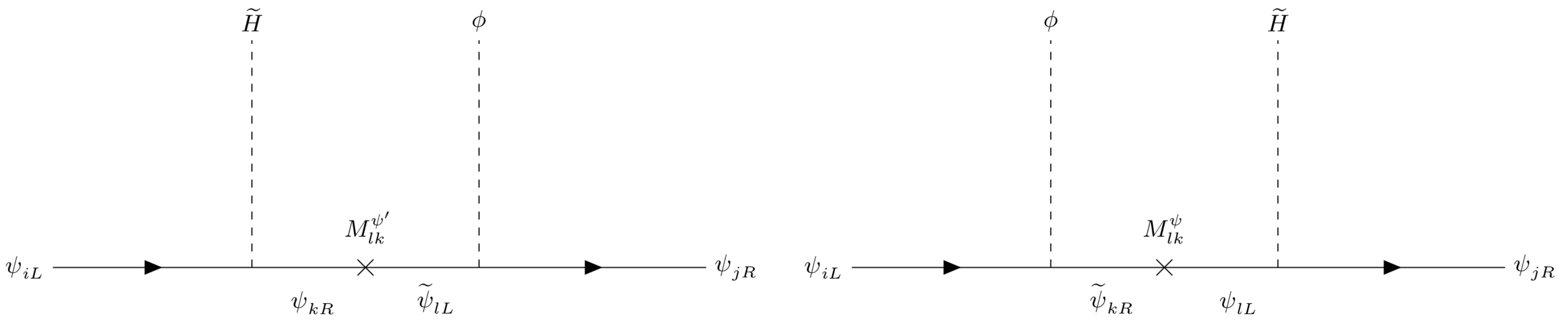


Figure 2: Diagrams in this model which lead to the effective Yukawa interactions, where $\psi, \psi' = Q, u, d, L, e$(neutrinos will be treated separately) $i, j = 1, 2, 3$, $k, l = 4$, M_{lk} is vectorlike mass and $\widetilde{H} = i\sigma_2 H^*, H = H_{u,d}$

daniele.rizzo@ncbj.gov.pl
Daniele Rizzo

Type-II next-to-2HDM

Field	Q_{iL}	u_{iR}	d_{iR}	L_{iL}	e_{iR}	Q_{kL}	u_{kR}	d_{kR}	L_{kL}	e_{kR}	ν_{kR}	$\widetilde{Q}_{kR}$	$\widetilde{u}_{kL}$	$\widetilde{d}_{kL}$	$\widetilde{L}_{kR}$	$\widetilde{e}_{kL}$	$\widetilde{\nu}_{kR}$	ϕ	H_u	H_d
$SU(3)_C$	**3**	**3**	**3**	**1**	**1**	**3**	**3**	**3**	**1**	**1**	**1**	**3**	**3**	**3**	**1**	**1**	**1**	**1**	**1**	**1**
$SU(2)_L$	**2**	**1**	**1**	**2**	**1**	**2**	**1**	**1**	**2**	**1**	**1**	**2**	**1**	**1**	**2**	**1**	**1**	**1**	**2**	**2**
$U(1)_Y$	$\frac{1}{6}$	$\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{1}{2}$	1	$\frac{1}{6}$	$\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{1}{2}$	-1	0	$\frac{1}{6}$	$\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{1}{2}$	-1	0	0	$\frac{1}{2}$	$-\frac{1}{2}$
$U(1)'$	0	0	0	0	0	1	-1	-1	1	-1	-1	1	-1	-1	1	-1	-1	1	-1	-1

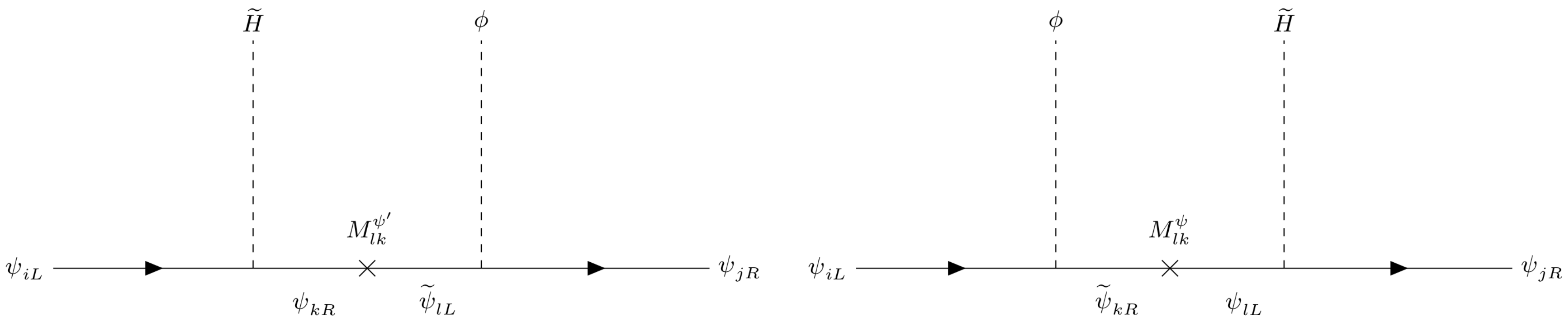


Figure 2: Diagrams in this model which lead to the effective Yukawa interactions, where $\psi, \psi' = Q, u, d, L, e$(neutrinos will be treated separately) $i, j = 1, 2, 3,\ k, l = 4,\ M_{lk}$ is vectorlike mass and $\widetilde{H} = i\sigma_2 H^*, H = H_{u,d}$

daniele.rizzo@ncbj.gov.pl
Daniele Rizzo

Type-II next-to-2HDM

Field	Q_{iL}	u_{iR}	d_{iR}	L_{iL}	e_{iR}	Q_{kL}	u_{kR}	d_{kR}	L_{kL}	e_{kR}	ν_{kR}	$\widetilde{Q}_{kR}$	$\widetilde{u}_{kL}$	$\widetilde{d}_{kL}$	$\widetilde{L}_{kR}$	$\widetilde{e}_{kL}$	$\widetilde{\nu}_{kR}$	ϕ	H_u	H_d
$SU(3)_C$	**3**	**3**	**3**	**1**	**1**	**3**	**3**	**3**	**1**	**1**	**1**	**3**	**3**	**3**	**1**	**1**	**1**	**1**	**1**	**1**
$SU(2)_L$	**2**	**1**	**1**	**2**	**1**	**2**	**1**	**1**	**2**	**1**	**1**	**2**	**1**	**1**	**2**	**1**	**1**	**1**	**2**	**2**
$U(1)_Y$	$\frac{1}{6}$	$\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{1}{2}$	1	$\frac{1}{6}$	$\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{1}{2}$	-1	0	$\frac{1}{6}$	$\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{1}{2}$	-1	0	0	$\frac{1}{2}$	$-\frac{1}{2}$
$U(1)'$	0	0	0	0	0	1	-1	-1	1	-1	-1	1	-1	-1	1	-1	-1	1	-1	-1

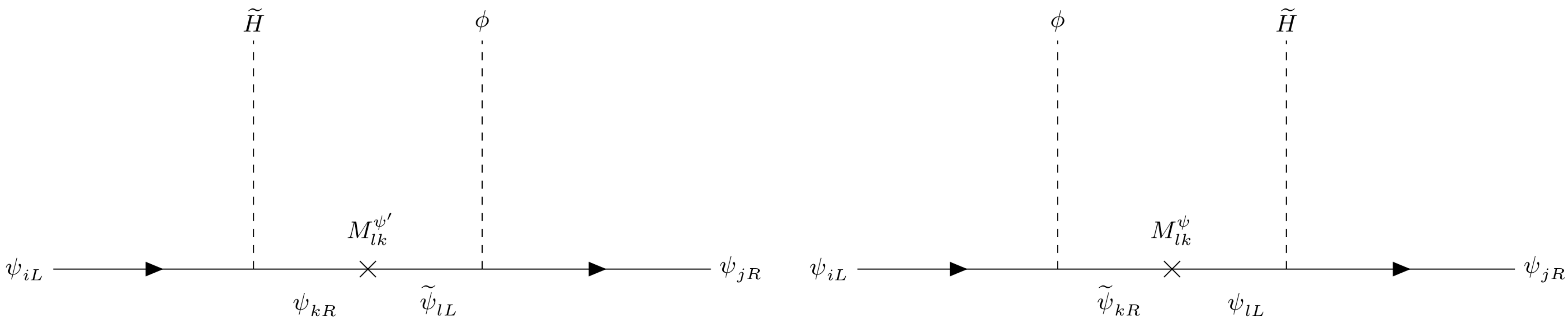


Figure 2: Diagrams in this model which lead to the effective Yukawa interactions, where $\psi, \psi' = Q, u, d, L, e$(neutrinos will be treated separately) $i, j = 1, 2, 3$, $k, l = 4$, M_{lk} is vectorlike mass and $\widetilde{H} = i\sigma_2 H^*, H = H_{u,d}$

daniele.rizzo@ncbj.gov.pl

Daniele Rizzo

The seesaw mechanism

Mass generation

Type-II next-to-2HDM

Mass generation

$$M^{\psi} = \left(\begin{array}{c|ccccc} & \psi_{1R} & \psi_{2R} & \psi_{3R} & \psi_{4R} & \widetilde{\psi}_{4R} \\ \hline \overline{\psi}_{1L} & 0 & 0 & 0 & y^{\psi}_{14}\langle \widetilde{H}^0 \rangle & x^{\psi}_{14}\langle \phi \rangle \\ \overline{\psi}_{2L} & 0 & 0 & 0 & y^{\psi}_{24}\langle \widetilde{H}^0 \rangle & x^{\psi}_{24}\langle \phi \rangle \\ \overline{\psi}_{3L} & 0 & 0 & 0 & y^{\psi}_{34}\langle \widetilde{H}^0 \rangle & x^{\psi}_{34}\langle \phi \rangle \\ \overline{\psi}_{4L} & y^{\psi}_{41}\langle \widetilde{H}^0 \rangle & y^{\psi}_{42}\langle \widetilde{H}^0 \rangle & y^{\psi}_{43}\langle \widetilde{H}^0 \rangle & 0 & M^{\psi}_{44} \\ \overline{\widetilde{\psi}}_{4L} & x^{\psi\prime}_{41}\langle \phi \rangle & x^{\psi\prime}_{42}\langle \phi \rangle & x^{\psi\prime}_{43}\langle \phi \rangle & M^{\psi\prime}_{44} & 0 \end{array}\right)$$

daniele.rizzo@ncbj.gov.pl
Daniele Rizzo

The seesaw mechanism

Mass generation

$$A = \begin{pmatrix} 0 & M \\ M & B \end{pmatrix}$$

daniele.rizzo@ncbj.gov.pl Daniele Rizzo

The seesaw mechanism

Mass generation

$$A = \begin{pmatrix} 0 & M \\ M & B \end{pmatrix}$$

$$\lambda_- = \frac{B - \sqrt{B^2 + 4M^2}}{2} \approx \frac{M^2}{B} + O\left(\frac{2M^2}{B}\right)$$

$$\lambda_+ = \frac{B + \sqrt{B^2 + 4M^2}}{2} \approx B + \frac{M^2}{B} + O\left(\frac{2M^2}{B}\right)$$

daniele.rizzo@ncbj.gov.pl
Daniele Rizzo

Type-II next-to-2HDM

Mass generation

$$M^{\psi} = \left(\begin{array}{c|ccccc} & \psi_{1R} & \psi_{2R} & \psi_{3R} & \psi_{4R} & \widetilde{\psi}_{4R} \\ \hline \overline{\psi}_{1L} & 0 & 0 & 0 & y^{\psi}_{14}\langle \widetilde{H}^0 \rangle & x^{\psi}_{14}\langle \phi \rangle \\ \overline{\psi}_{2L} & 0 & 0 & 0 & y^{\psi}_{24}\langle \widetilde{H}^0 \rangle & x^{\psi}_{24}\langle \phi \rangle \\ \overline{\psi}_{3L} & 0 & 0 & 0 & y^{\psi}_{34}\langle \widetilde{H}^0 \rangle & x^{\psi}_{34}\langle \phi \rangle \\ \overline{\psi}_{4L} & y^{\psi}_{41}\langle \widetilde{H}^0 \rangle & y^{\psi}_{42}\langle \widetilde{H}^0 \rangle & y^{\psi}_{43}\langle \widetilde{H}^0 \rangle & 0 & M^{\psi}_{44} \\ \overline{\widetilde{\psi}}_{4L} & x^{\psi\prime}_{41}\langle \phi \rangle & x^{\psi\prime}_{42}\langle \phi \rangle & x^{\psi\prime}_{43}\langle \phi \rangle & M^{\psi\prime}_{44} & 0 \end{array} \right)$$

daniele.rizzo@ncbj.gov.pl
Daniele Rizzo

Type-II next-to-2HDM

Mass generation

$$M^{e\prime} = \mathrm{diag}\left(0, m_\mu, m_\tau, M_{E_4}, M_{\widetilde{E}_4}\right)$$

$$M^{u\prime} = \mathrm{diag}\left(0, m_c, m_t, M_{U_4}, M_{\widetilde{U}_4}\right)$$

$$M^{d\prime} = \mathrm{diag}\left(0, m_s, m_b, M_{D_4}, M_{\widetilde{D}_4}\right)$$

daniele.rizzo@ncbj.gov.pl
Daniele Rizzo

Type-II next-to-2HDM

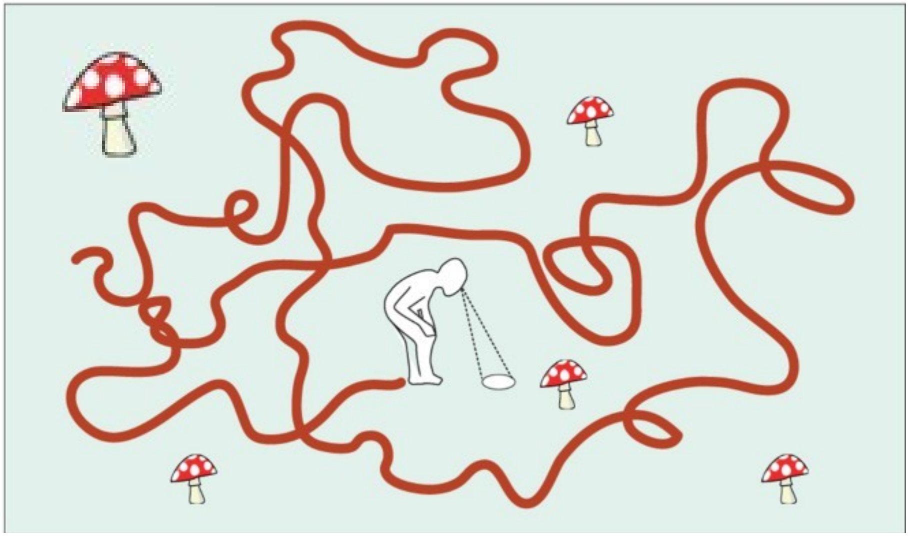
$$\chi^2 = \frac{(m_h^{\rm Thy} - m_h^{\rm Cen})^2}{(\delta m_h^{\rm Dev})^2} + \frac{(\Delta M_W^{\rm Thy} - \Delta M_W^{\rm Cen})^2}{(\delta \Delta M_W^{\rm Dev})^2} + \frac{(m_\mu^{\rm Thy} - m_\mu^{\rm Cen})^2}{(\delta m_\mu^{\rm Dev})^2} + \frac{(m_\tau^{\rm Thy} - m_\tau^{\rm Cen})^2}{(\delta m_\tau^{\rm Dev})^2}$$
$$+ \frac{(a_{hWW}^{\rm Thy} - a_{hWW}^{\rm Cen})^2}{(\delta a_{hWW}^{\rm Dev})^2} + \frac{(R_{\gamma\gamma}^{\rm Thy} - R_{\gamma\gamma}^{\rm Cen})^2}{(\delta R_{\gamma\gamma}^{\rm Dev})^2} + \frac{(\Delta a_\mu^{\rm Thy} - \Delta a_\mu^{\rm Cen})^2}{(\delta \Delta a_\mu^{\rm Dev})^2} +$$
$$+ \frac{(\Delta S^{\rm Thy} - \Delta S^{\rm Cen})^2}{(\delta \Delta S^{\rm Dev})^2} + \frac{(\Delta T^{\rm Thy} - \Delta T^{\rm Cen})^2}{(\delta \Delta T^{\rm Dev})^2} + \frac{(\Delta U^{\rm Thy} - \Delta U^{\rm Cen})^2}{(\delta \Delta U^{\rm Dev})^2}$$

daniele.rizzo@ncbj.gov.pl
Daniele Rizzo

Type-II next-to-2HDM

$$\chi^2 = \frac{(m_h^{\rm Thy} - m_h^{\rm Cen})^2}{(\delta m_h^{\rm Dev})^2} + \frac{(\Delta M_W^{\rm Thy} - \Delta M_W^{\rm Cen})^2}{(\delta \Delta M_W^{\rm Dev})^2} + \frac{(m_\mu^{\rm Thy} - m_\mu^{\rm Cen})^2}{(\delta m_\mu^{\rm Dev})^2} + \frac{(m_\tau^{\rm Thy} - m_\tau^{\rm Cen})^2}{(\delta m_\tau^{\rm Dev})^2}$$
$$+ \frac{(a_{hWW}^{\rm Thy} - a_{hWW}^{\rm Cen})^2}{(\delta a_{hWW}^{\rm Dev})^2} + \frac{(R_{\gamma\gamma}^{\rm Thy} - R_{\gamma\gamma}^{\rm Cen})^2}{(\delta R_{\gamma\gamma}^{\rm Dev})^2} + \frac{(\Delta a_\mu^{\rm Thy} - \Delta a_\mu^{\rm Cen})^2}{(\delta \Delta a_\mu^{\rm Dev})^2} +$$
$$+ \frac{(\Delta S^{\rm Thy} - \Delta S^{\rm Cen})^2}{(\delta \Delta S^{\rm Dev})^2} + \frac{(\Delta T^{\rm Thy} - \Delta T^{\rm Cen})^2}{(\delta \Delta T^{\rm Dev})^2} + \frac{(\Delta U^{\rm Thy} - \Delta U^{\rm Cen})^2}{(\delta \Delta U^{\rm Dev})^2}$$

Random walk algorithm

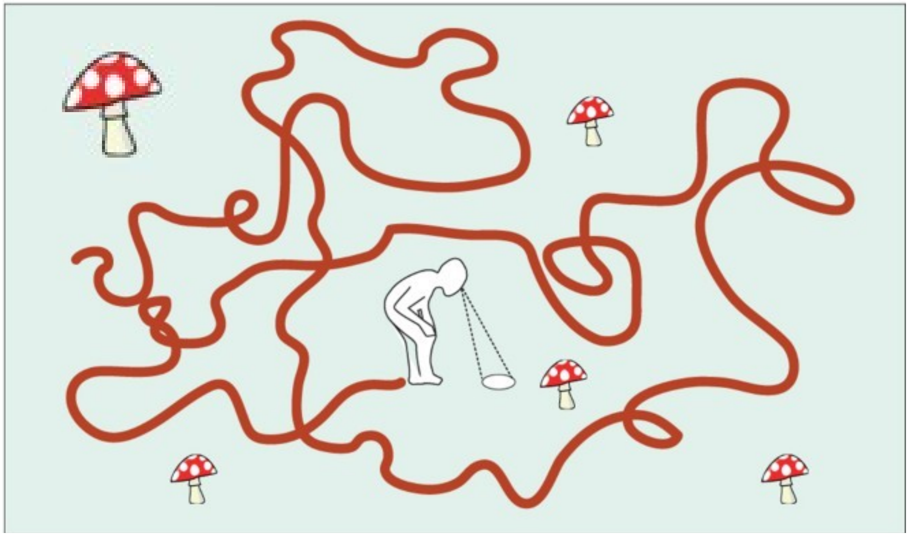


daniele.rizzo@ncbj.gov.pl Daniele Rizzo

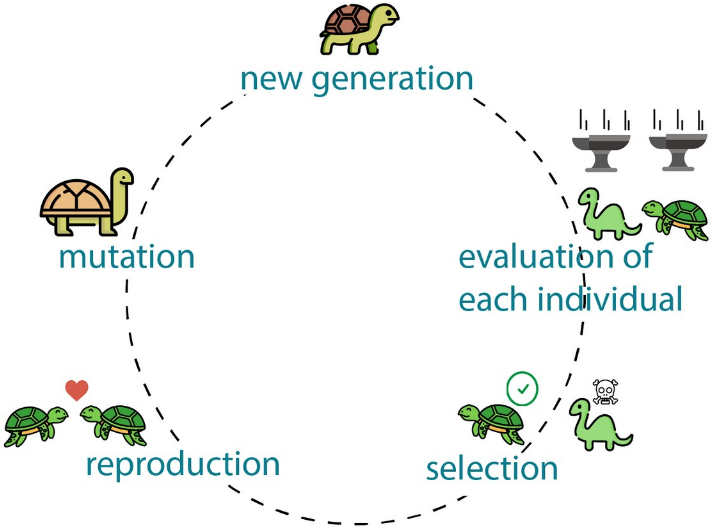
Type-II next-to-2HDM

$$\chi^2 = \frac{(m_h^{\rm Thy} - m_h^{\rm Cen})^2}{(\delta m_h^{\rm Dev})^2} + \frac{(\Delta M_W^{\rm Thy} - \Delta M_W^{\rm Cen})^2}{(\delta \Delta M_W^{\rm Dev})^2} + \frac{(m_\mu^{\rm Thy} - m_\mu^{\rm Cen})^2}{(\delta m_\mu^{\rm Dev})^2} + \frac{(m_\tau^{\rm Thy} - m_\tau^{\rm Cen})^2}{(\delta m_\tau^{\rm Dev})^2}$$
$$+ \frac{(a_{hWW}^{\rm Thy} - a_{hWW}^{\rm Cen})^2}{(\delta a_{hWW}^{\rm Dev})^2} + \frac{(R_{\gamma\gamma}^{\rm Thy} - R_{\gamma\gamma}^{\rm Cen})^2}{(\delta R_{\gamma\gamma}^{\rm Dev})^2} + \frac{(\Delta a_\mu^{\rm Thy} - \Delta a_\mu^{\rm Cen})^2}{(\delta \Delta a_\mu^{\rm Dev})^2} +$$
$$+ \frac{(\Delta S^{\rm Thy} - \Delta S^{\rm Cen})^2}{(\delta \Delta S^{\rm Dev})^2} + \frac{(\Delta T^{\rm Thy} - \Delta T^{\rm Cen})^2}{(\delta \Delta T^{\rm Dev})^2} + \frac{(\Delta U^{\rm Thy} - \Delta U^{\rm Cen})^2}{(\delta \Delta U^{\rm Dev})^2}$$

Random walk algorithm



Genetic algorithm



daniele.rizzo@ncbj.gov.pl
Daniele Rizzo

Type-II next-to-2HDM

11 free parameters

$$
\begin{aligned}
V &= \mu_1^2(H_u^\dagger H_u) + \mu_2^2(H_d^\dagger H_d) + \mu_3^2(\phi^*\phi) \\
&+ \frac{1}{2}\lambda_1(H_u^\dagger H_u)^2 + \frac{1}{2}\lambda_2(H_d^\dagger H_d)^2 + \lambda_3(H_u^\dagger H_u)(H_d^\dagger H_d) + \lambda_4(H_u^\dagger H_d)(H_d^\dagger H_u) \\
&+ \frac{1}{2}\lambda_5(\epsilon_{ij}H_u^i H_d^j \phi^2 + H.c.) + \frac{1}{2}\lambda_6(\phi^*\phi)^2 + \lambda_7(\phi^*\phi)(H_u^\dagger H_u) + \lambda_8(\phi^*\phi)(H_d^\dagger H_d),
\end{aligned}
$$

daniele.rizzo@ncbj.gov.pl

Daniele Rizzo

Type-II next-to-2HDM

11 free parameters

$$V = \mu_1^2(H_u^\dagger H_u) + \mu_2^2(H_d^\dagger H_d) + \mu_3^2(\phi^*\phi)$$
$$+ \frac{1}{2}\lambda_1(H_u^\dagger H_u)^2 + \frac{1}{2}\lambda_2(H_d^\dagger H_d)^2 + \lambda_3(H_u^\dagger H_u)(H_d^\dagger H_d) + \lambda_4(H_u^\dagger H_d)(H_d^\dagger H_u)$$
$$+ \frac{1}{2}\lambda_5(\epsilon_{ij}H_u^i H_d^j \phi^2 + H.c.) + \frac{1}{2}\lambda_6(\phi^*\phi)^2 + \lambda_7(\phi^*\phi)(H_u^\dagger H_u) + \lambda_8(\phi^*\phi)(H_d^\dagger H_d),$$

$$H_u = \begin{pmatrix} H_u^+ \\ \frac{1}{\sqrt{2}}\left(v_u + \mathrm{Re}\, H_u^0 + i\, \mathrm{Im}\, H_u^0\right) \end{pmatrix}, \qquad H_d = \begin{pmatrix} \frac{1}{\sqrt{2}}\left(v_d + \mathrm{Re}\, H_d^0 + i\, \mathrm{Im}\, H_d^0\right) \\ H_d^- \end{pmatrix},$$

$$\phi = \frac{1}{\sqrt{2}}\left(v_\phi + \mathrm{Re}\,\phi + i\,\mathrm{Im}\,\phi\right).$$

$$\mu_1^2 = \frac{1}{2}\left(-\lambda_1 v_1^2 - \lambda_3 v_2^2\right), \qquad \mu_2^2 = \frac{1}{2}\left(\lambda_3 v_1^2 - \lambda_2 v_2^2 - \lambda_8 v_3^2\right),$$

$$\mu_3^2 = \frac{\lambda_3 v_1^2 v_2^2}{v_3^2} - \frac{1}{2}\lambda_8 v_2^2 - \frac{1}{2}\lambda_6 v_3^2.$$

daniele.rizzo@ncbj.gov.pl Daniele Rizzo

Type-II next-to-2HDM

11 free parameters

$$V = \mu_1^2(H_u^\dagger H_u) + \mu_2^2(H_d^\dagger H_d) + \mu_3^2(\phi^*\phi)$$
$$+ \frac{1}{2}\lambda_1(H_u^\dagger H_u)^2 + \frac{1}{2}\lambda_2(H_d^\dagger H_d)^2 + \lambda_3(H_u^\dagger H_u)(H_d^\dagger H_d) + \lambda_4(H_u^\dagger H_d)(H_d^\dagger H_u)$$
$$+ \frac{1}{2}\lambda_5(\epsilon_{ij}H_u^i H_d^j \phi^2 + H.c.) + \frac{1}{2}\lambda_6(\phi^*\phi)^2 + \lambda_7(\phi^*\phi)(H_u^\dagger H_u) + \lambda_8(\phi^*\phi)(H_d^\dagger H_d),$$

$$\mathbf{M}^2_{\text{CP-even}} = \begin{pmatrix} v_1^2\lambda_1 - \frac{v_2 v_3^2 \lambda_5}{4v_1} & \frac{1}{4}\lambda_5 v_3^2 + v_1 v_2 \lambda_3 & \frac{1}{2}v_3\left(v_2\lambda_5 + 2v_1\lambda_7\right) \\ \frac{1}{4}\lambda_5 v_3^2 + v_1 v_2\lambda_3 & v_2^2\lambda_2 - \frac{v_1 v_3^2\lambda_5}{4v_2} & \frac{1}{2}v_3\left(v_1\lambda_5 + 2v_2\lambda_8\right) \\ \frac{1}{2}v_3\left(v_2\lambda_5 + 2v_1\lambda_7\right) & \frac{1}{2}v_3\left(v_1\lambda_5 + 2v_2\lambda_8\right) & v_3^2\lambda_6 \end{pmatrix},$$

daniele.rizzo@ncbj.gov.pl
Daniele Rizzo

Type-II next-to-2HDM

8 free parameters

$$V = \mu_1^2(H_u^\dagger H_u) + \mu_2^2(H_d^\dagger H_d) + \mu_3^2(\phi^*\phi)$$
$$+ \frac{1}{2}\lambda_1(H_u^\dagger H_u)^2 + \frac{1}{2}\lambda_2(H_d^\dagger H_d)^2 + \lambda_3(H_u^\dagger H_u)(H_d^\dagger H_d) + \lambda_4(H_u^\dagger H_d)(H_d^\dagger H_u)$$
$$+ \frac{1}{2}\lambda_5(\epsilon_{ij}H_u^i H_d^j \phi^2 + H.c.) + \frac{1}{2}\lambda_6(\phi^*\phi)^2 + \lambda_7(\phi^*\phi)(H_u^\dagger H_u) + \lambda_8(\phi^*\phi)(H_d^\dagger H_d),$$

$$\mathbf{M}^2_{\text{CP-even}} = \begin{pmatrix} M_H^2 & 0 & 0 \\ 0 & \lambda_3 v_1^2 + v_2^2\lambda_2 & -\frac{1}{2}v_3\left(\frac{4v_1^2 v_2\lambda_3}{v_3^2} - 2v_2\lambda_8\right) \\ 0 & -\frac{1}{2}v_3\left(\frac{4v_1^2 v_2\lambda_3}{v_3^2} - 2v_2\lambda_8\right) & v_3^2\lambda_6 \end{pmatrix}.$$

$$\lambda_5 = -\frac{4v_1 v_2}{v_3^2}\lambda_3, \qquad \lambda_7 = -\frac{v_2}{2v_1}\lambda_5 = \frac{2v_2^2}{v_3^2}\lambda_3. \qquad \lambda_1 = \frac{M_H^2 - v_2^2\lambda_3}{v_1^2}$$

daniele.rizzo@ncbj.gov.pl Daniele Rizzo

Type-II next-to-2HDM

6 free parameters

$$V = \mu_1^2(H_u^\dagger H_u) + \mu_2^2(H_d^\dagger H_d) + \mu_3^2(\phi^*\phi)$$
$$+ \frac{1}{2}\lambda_1(H_u^\dagger H_u)^2 + \frac{1}{2}\lambda_2(H_d^\dagger H_d)^2 + \lambda_3(H_u^\dagger H_u)(H_d^\dagger H_d) + \lambda_4(H_u^\dagger H_d)(H_d^\dagger H_u)$$
$$+ \frac{1}{2}\lambda_5(\epsilon_{ij}H_u^i H_d^j \phi^2 + H.c.) + \frac{1}{2}\lambda_6(\phi^*\phi)^2 + \lambda_7(\phi^*\phi)(H_u^\dagger H_u) + \lambda_8(\phi^*\phi)(H_d^\dagger H_d),$$

$$\mathbf{M}^2_{\text{CP-even}} = \begin{pmatrix} M_H^2 & 0 & 0 \\ 0 & \lambda_3 v_1^2 + v_2^2\lambda_2 & -\frac{1}{2}v_3\left(\frac{4v_1^2 v_2\lambda_3}{v_3^2} - 2v_2\lambda_8\right) \\ 0 & -\frac{1}{2}v_3\left(\frac{4v_1^2 v_2\lambda_3}{v_3^2} - 2v_2\lambda_8\right) & v_3^2\lambda_6 \end{pmatrix}.$$

$$\lambda_5 = -\frac{4v_1v_2}{v_3^2}\lambda_3, \qquad \lambda_7 = -\frac{v_2}{2v_1}\lambda_5 = \frac{2v_2^2}{v_3^2}\lambda_3. \qquad \lambda_1 = \frac{M_H^2 - v_2^2\lambda_3}{v_1^2}$$

$$v_1 = \frac{\tan\beta}{\sqrt{1+\tan^2\beta}}\frac{v}{\sqrt{2}} \qquad v_2 = \frac{1}{\sqrt{1+\tan^2\beta}}\frac{v}{\sqrt{2}} \qquad \tan\beta = 50$$

daniele.rizzo@ncbj.gov.pl
Daniele Rizzo

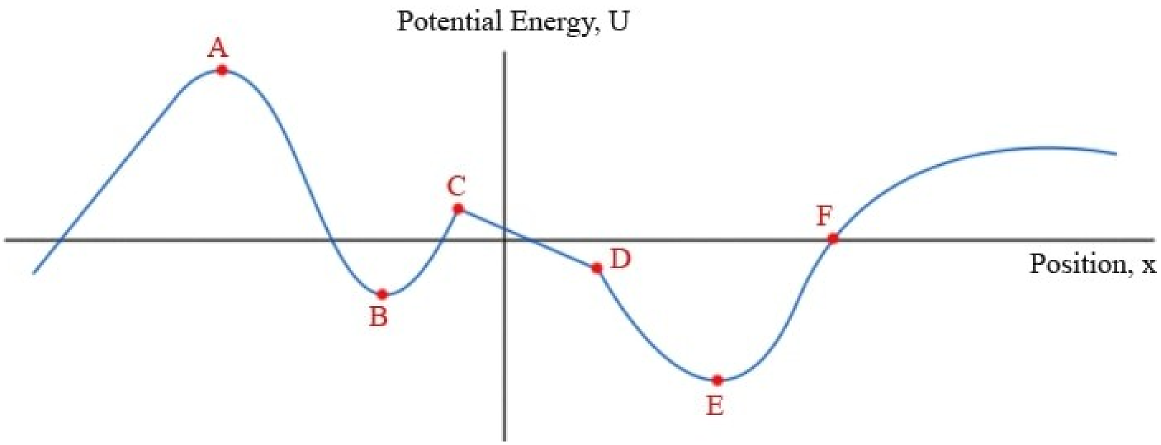
Type-II next-to-2HDM

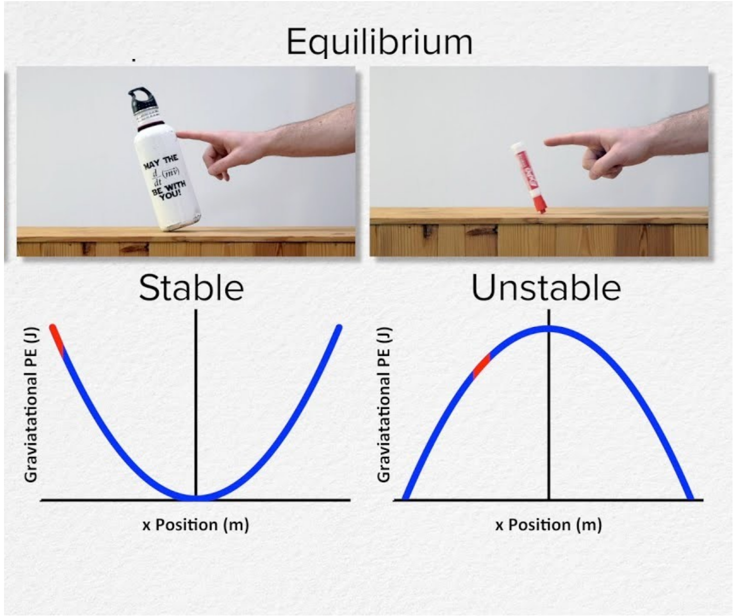
$$V = \mu_1^2(H_u^\dagger H_u) + \mu_2^2(H_d^\dagger H_d) + \mu_3^2(\phi^*\phi)$$
$$+ \frac{1}{2}\lambda_1(H_u^\dagger H_u)^2 + \frac{1}{2}\lambda_2(H_d^\dagger H_d)^2 + \lambda_3(H_u^\dagger H_u)(H_d^\dagger H_d) + \lambda_4(H_u^\dagger H_d)(H_d^\dagger H_u)$$
$$+ \frac{1}{2}\lambda_5(\epsilon_{ij}H_u^i H_d^j \phi^2 + H.c.) + \frac{1}{2}\lambda_6(\phi^*\phi)^2 + \lambda_7(\phi^*\phi)(H_u^\dagger H_u) + \lambda_8(\phi^*\phi)(H_d^\dagger H_d),$$

daniele.rizzo@ncbj.gov.pl Daniele Rizzo

Type-II next-to-2HDM

$$V = \mu_1^2(H_u^\dagger H_u) + \mu_2^2(H_d^\dagger H_d) + \mu_3^2(\phi^*\phi)$$
$$+ \frac{1}{2}\lambda_1(H_u^\dagger H_u)^2 + \frac{1}{2}\lambda_2(H_d^\dagger H_d)^2 + \lambda_3(H_u^\dagger H_u)(H_d^\dagger H_d) + \lambda_4(H_u^\dagger H_d)(H_d^\dagger H_u)$$
$$+ \frac{1}{2}\lambda_5(\epsilon_{ij}H_u^i H_d^j \phi^2 + H.c.) + \frac{1}{2}\lambda_6(\phi^*\phi)^2 + \lambda_7(\phi^*\phi)(H_u^\dagger H_u) + \lambda_8(\phi^*\phi)(H_d^\dagger H_d),$$

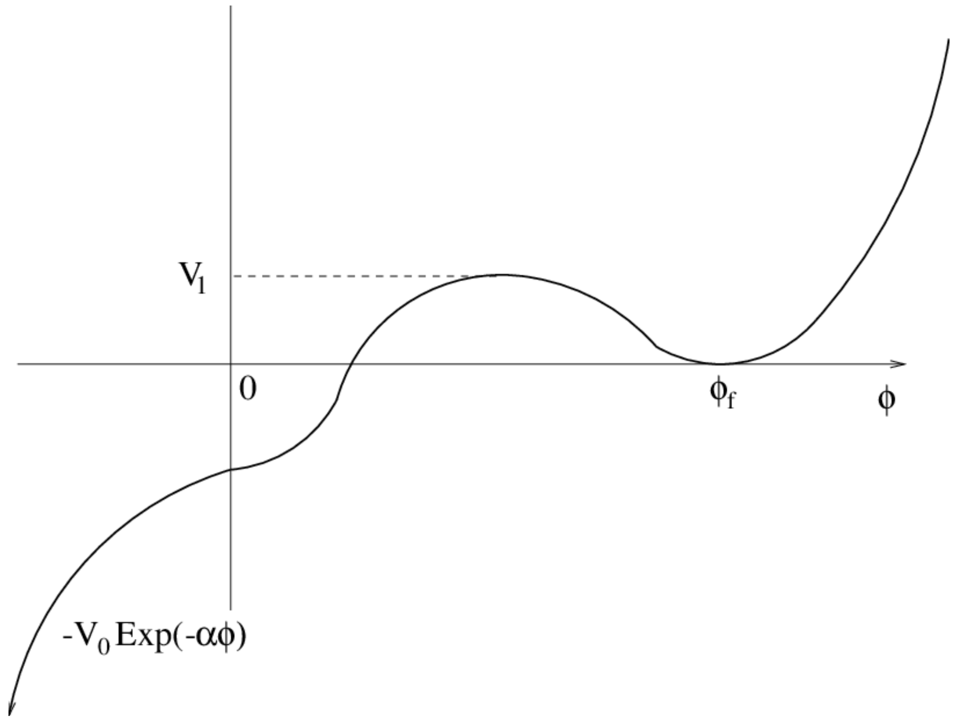




daniele.rizzo@ncbj.gov.pl
Daniele Rizzo

Type-II next-to-2HDM

$$V = \mu_1^2(H_u^\dagger H_u) + \mu_2^2(H_d^\dagger H_d) + \mu_3^2(\phi^*\phi)$$
$$+ \frac{1}{2}\lambda_1(H_u^\dagger H_u)^2 + \frac{1}{2}\lambda_2(H_d^\dagger H_d)^2 + \lambda_3(H_u^\dagger H_u)(H_d^\dagger H_d) + \lambda_4(H_u^\dagger H_d)(H_d^\dagger H_u)$$
$$+ \frac{1}{2}\lambda_5(\epsilon_{ij}H_u^i H_d^j \phi^2 + H.c.) + \frac{1}{2}\lambda_6(\phi^*\phi)^2 + \lambda_7(\phi^*\phi)(H_u^\dagger H_u) + \lambda_8(\phi^*\phi)(H_d^\dagger H_d),$$



Type-II next-to-2HDM

$$V_4 = \frac{1}{2}\lambda_1(H_u^\dagger H_u)^2 + \frac{1}{2}\lambda_2(H_d^\dagger H_d)^2 + \lambda_3(H_u^\dagger H_u)(H_d^\dagger H_d) + \lambda_4(H_u^\dagger H_d)(H_d^\dagger H_u)$$
$$+ \frac{1}{2}\lambda_5(\epsilon_{ij}H_u^i H_d^j \phi^2 + \mathrm{H.c.}) + \frac{1}{2}\lambda_6(\phi^*\phi)^2 + \lambda_7(\phi^*\phi)(H_u^\dagger H_u) + \lambda_8(\phi^*\phi)(H_d^\dagger H_d)$$

2HDM: G. Bhattacharyya and D. Das, Pramana 87, no.3, 40

daniele.rizzo@ncbj.gov.pl

Daniele Rizzo

Type-II next-to-2HDM

$$V_4 = \frac{1}{2}\lambda_1(H_u^\dagger H_u)^2 + \frac{1}{2}\lambda_2(H_d^\dagger H_d)^2 + \lambda_3(H_u^\dagger H_u)(H_d^\dagger H_d) + \lambda_4(H_u^\dagger H_d)(H_d^\dagger H_u)$$
$$+ \frac{1}{2}\lambda_5(\epsilon_{ij}H_u^i H_d^j \phi^2 + \mathrm{H.c.}) + \frac{1}{2}\lambda_6(\phi^*\phi)^2 + \lambda_7(\phi^*\phi)(H_u^\dagger H_u) + \lambda_8(\phi^*\phi)(H_d^\dagger H_d)$$

$$a = H_u^\dagger H_u,$$
$$b = H_d^\dagger H_d,$$
$$c = \phi^*\phi,$$

$$d = \mathrm{Re}\, H_u^\dagger H_d,$$
$$e = \mathrm{Im}\, H_u^\dagger H_d,$$
$$f = \mathrm{Re}\, \epsilon_{ij} H_u^i H_d^j \phi^2,$$
$$g = \mathrm{Im}\, \epsilon_{ij} H_u^i H_d^j \phi^2,$$

daniele.rizzo@ncbj.gov.pl
Daniele Rizzo

Type-II next-to-2HDM

$$V_4 = \frac{1}{2}\left(\lambda_1 a^2 + 2\lambda_3 ab + \lambda_2 b^2\right) + \lambda_4\left(d^2 + e^2\right) +$$
$$+ \left(\mathrm{Re}\,\lambda_5 f - \mathrm{Im}\,\lambda_5 g\right) + \frac{1}{2}\left(\lambda_6 c^2 + 2\lambda_7 ca + 2\lambda_8 cb\right)$$

$$\begin{aligned}
a &= H_u^\dagger H_u, \\
b &= H_d^\dagger H_d, \\
c &= \phi^* \phi, \\
d &= \mathrm{Re}\, H_u^\dagger H_d, \\
e &= \mathrm{Im}\, H_u^\dagger H_d, \\
f &= \mathrm{Re}\, \epsilon_{ij} H_u^i H_d^j \phi^2, \\
g &= \mathrm{Im}\, \epsilon_{ij} H_u^i H_d^j \phi^2,
\end{aligned}$$

daniele.rizzo@ncbj.gov.pl
Daniele Rizzo

Type-II next-to-2HDM

$$V_4 = \frac{1}{2}\left(\lambda_1 a^2 + 2\lambda_3 ab + \lambda_2 b^2\right) + \lambda_4\left(d^2 + e^2\right) +$$
$$+ \left(\mathrm{Re}\,\lambda_5 f - \mathrm{Im}\,\lambda_5 g\right) + \frac{1}{2}\left(\lambda_6 c^2 + 2\lambda_7 ca + 2\lambda_8 cb\right)$$

$$a = H_u^\dagger H_u,$$
$$b = H_d^\dagger H_d,$$
$$c = \phi^* \phi,$$
$$d = \mathrm{Re}\, H_u^\dagger H_d,$$
$$e = \mathrm{Im}\, H_u^\dagger H_d,$$
$$f = \mathrm{Re}\,\epsilon_{ij} H_u^i H_d^j \phi^2,$$
$$g = \mathrm{Im}\,\epsilon_{ij} H_u^i H_d^j \phi^2,$$

Positivity conditions

$$ab \geq d^2 + e^2,$$
$$abc^2 \geq f^2 + g^2 \geq 2fg.$$

daniele.rizzo@ncbj.gov.pl

Daniele Rizzo

Type-II next-to-2HDM

$$V_4 = \frac{1}{2}\left(\lambda_1 a^2 + 2\lambda_3 ab + \lambda_2 b^2\right) + \lambda_4\left(d^2 + e^2\right) +$$
$$+ \left(\mathrm{Re}\,\lambda_5 f - \mathrm{Im}\,\lambda_5 g\right) + \frac{1}{2}\left(\lambda_6 c^2 + 2\lambda_7 ca + 2\lambda_8 cb\right)$$

$$a = H_u^\dagger H_u,$$
$$b = H_d^\dagger H_d,$$
$$c = \phi^*\phi,$$
$$d = \mathrm{Re}\, H_u^\dagger H_d,$$
$$e = \mathrm{Im}\, H_u^\dagger H_d,$$
$$f = \mathrm{Re}\,\epsilon_{ij} H_u^i H_d^j \phi^2,$$
$$g = \mathrm{Im}\,\epsilon_{ij} H_u^i H_d^j \phi^2,$$

When $a = 0$, then $d = e = f = g = 0$

$$V_4\left(a = d = e = f = g = 0\right) = \frac{1}{2}\lambda_2 b^2 + \frac{1}{2}\left(\sqrt{\lambda_6}c + \frac{\lambda_8 b}{\sqrt{\lambda_6}}\right)^2 - \frac{1}{2}\frac{(\lambda_8 b)^2}{\lambda_6} > 0$$

$$V_4\left(a = d = e = f = g = 0, \quad b = \sqrt{\frac{\lambda_6}{\lambda_2}}c\right) = \frac{1}{2}\left(\sqrt{\lambda_2}b - \sqrt{\lambda_6}c\right)^2 + \left(\lambda_8 + \sqrt{\lambda_2\lambda_6}\right)bc > 0$$

Positivity conditions

$$ab \geq d^2 + e^2,$$
$$abc^2 \geq f^2 + g^2 \geq 2fg.$$

daniele.rizzo@ncbj.gov.pl
Daniele Rizzo

Type-II next-to-2HDM

$$V_4 = \frac{1}{2}\left(\lambda_1 a^2 + 2\lambda_3 ab + \lambda_2 b^2\right) + \lambda_4\left(d^2 + e^2\right) + $$
$$+ \left(\mathrm{Re}\,\lambda_5 f - \mathrm{Im}\,\lambda_5 g\right) + \frac{1}{2}\left(\lambda_6 c^2 + 2\lambda_7 ca + 2\lambda_8 cb\right)$$

$$a = H_u^\dagger H_u,$$
$$b = H_d^\dagger H_d,$$
$$c = \phi^*\phi,$$
$$d = \mathrm{Re}\, H_u^\dagger H_d,$$
$$e = \mathrm{Im}\, H_u^\dagger H_d,$$
$$f = \mathrm{Re}\,\epsilon_{ij} H_u^i H_d^j \phi^2,$$
$$g = \mathrm{Im}\,\epsilon_{ij} H_u^i H_d^j \phi^2,$$

When $a = 0$, then $d = e = f = g = 0$

$$V_4\left(a = d = e = f = g = 0\right) = \frac{1}{2}\lambda_2 b^2 + \frac{1}{2}\left(\sqrt{\lambda_6}c + \frac{\lambda_8 b}{\sqrt{\lambda_6}}\right)^2 - \frac{1}{2}\frac{(\lambda_8 b)^2}{\lambda_6} > 0$$

$$V_4\left(a = d = e = f = g = 0, \quad b = \sqrt{\frac{\lambda_6}{\lambda_2}}c\right) = \frac{1}{2}\left(\sqrt{\lambda_2}b - \sqrt{\lambda_6}c\right)^2 + \left(\lambda_8 + \sqrt{\lambda_2\lambda_6}\right)bc > 0$$

When $b = 0$, then $d = e = f = g = 0$

$$V_4\left(b = d = e = f = g = 0\right) = \frac{1}{2}\lambda_1 a^2 + \frac{1}{2}\left(\sqrt{\lambda_6}c + \frac{\lambda_7 a}{\sqrt{\lambda_6}}\right)^2 - \frac{1}{2}\frac{(\lambda_7 a)^2}{\lambda_6} > 0$$

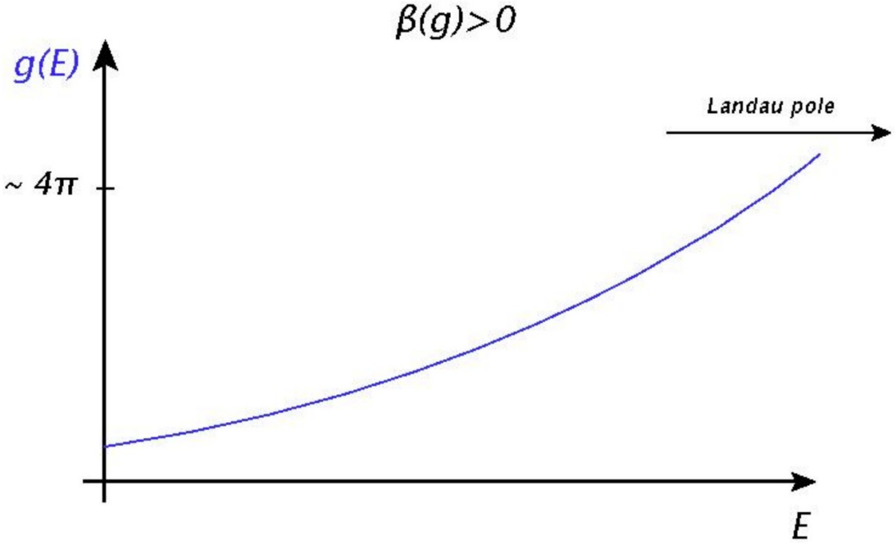
$$V_4\left(b = d = e = f = g = 0, \quad a = \sqrt{\frac{\lambda_6}{\lambda_1}}c\right) = \frac{1}{2}\left(\sqrt{\lambda_1}a - \sqrt{\lambda_6}c\right)^2 + \left(\lambda_7 + \sqrt{\lambda_1\lambda_6}\right)ac > 0$$

Positivity conditions

$$ab \geq d^2 + e^2,$$
$$abc^2 \geq f^2 + g^2 \geq 2fg.$$

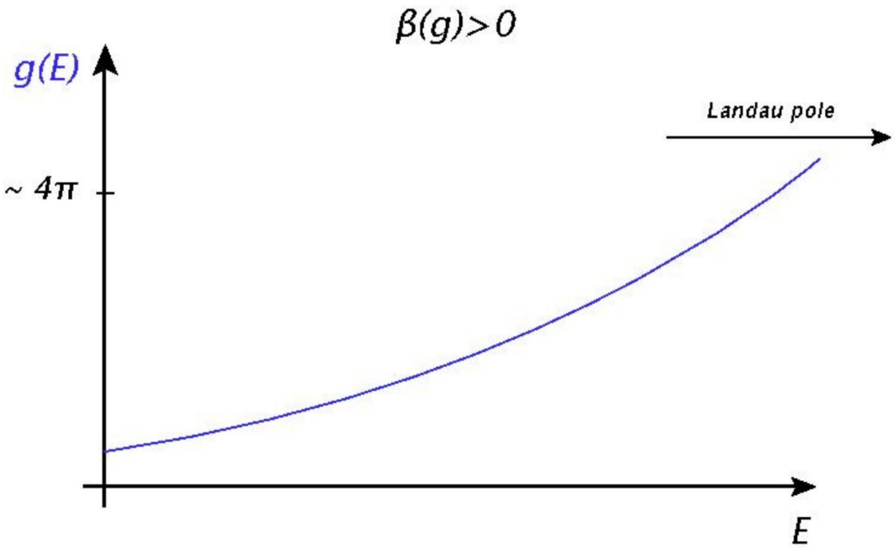
daniele.rizzo@ncbj.gov.pl
Daniele Rizzo

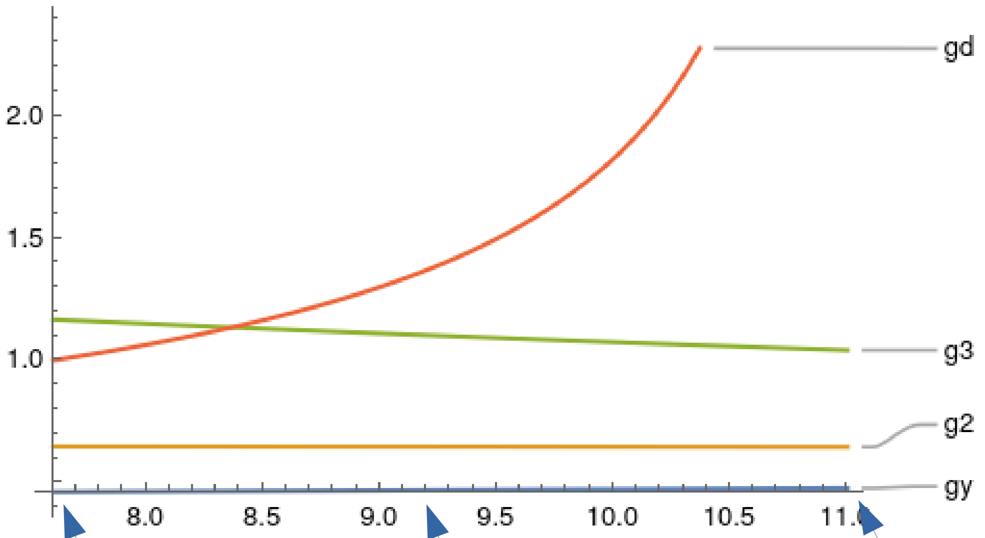
Type-II next-to-2HDM



daniele.rizzo@ncbj.gov.pl
Daniele Rizzo

Type-II next-to-2HDM





2 TeV

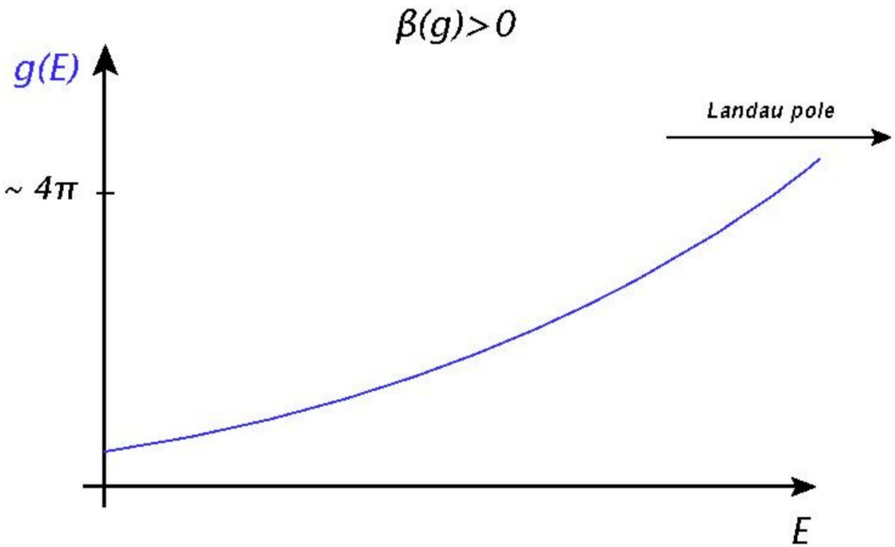
10 TeV

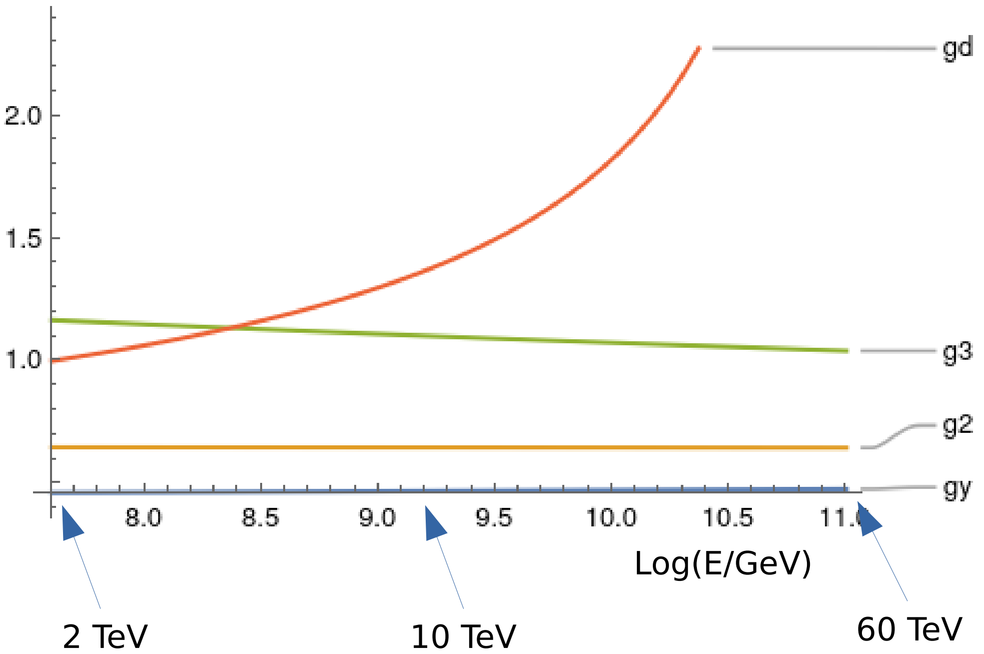
60 TeV

daniele.rizzo@ncbj.gov.pl

Daniele Rizzo

Type-II next-to-2HDM

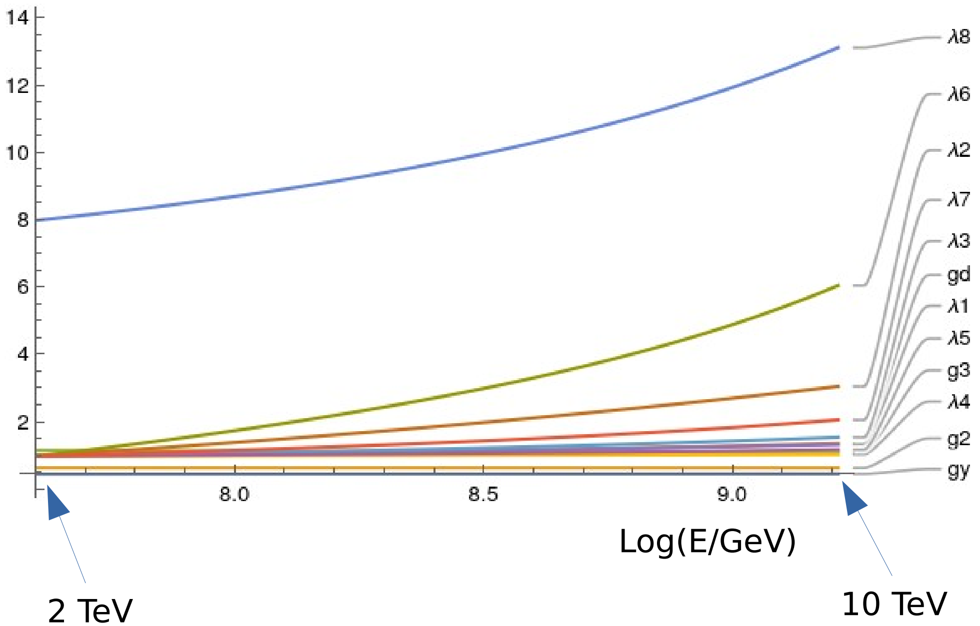




gd(2 TeV) = 1 → gd(10 TeV) = 1.37 → gd(60 TeV) = 10.41

daniele.rizzo@ncbj.gov.pl
Daniele Rizzo

Type-II next-to-2HDM



$\lambda_1(2\,\mathrm{TeV}) = 1$

$\lambda_2(2\,\mathrm{TeV}) = 1$

$\lambda_3(2\,\mathrm{TeV}) = 1$

$\lambda_4(2\,\mathrm{TeV}) = 1$

$\lambda_5(2\,\mathrm{TeV}) = 1$

$\lambda_6(2\,\mathrm{TeV}) = 1$

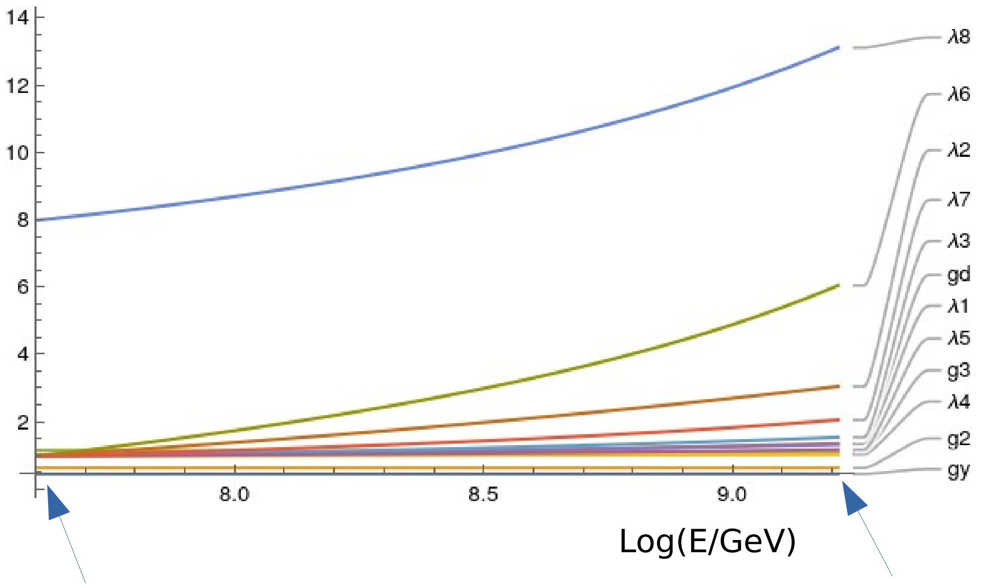
$\lambda_7(2\,\mathrm{TeV}) = 1$

$\lambda_8(2\,\mathrm{TeV}) = 8$

daniele.rizzo@ncbj.gov.pl

Daniele Rizzo

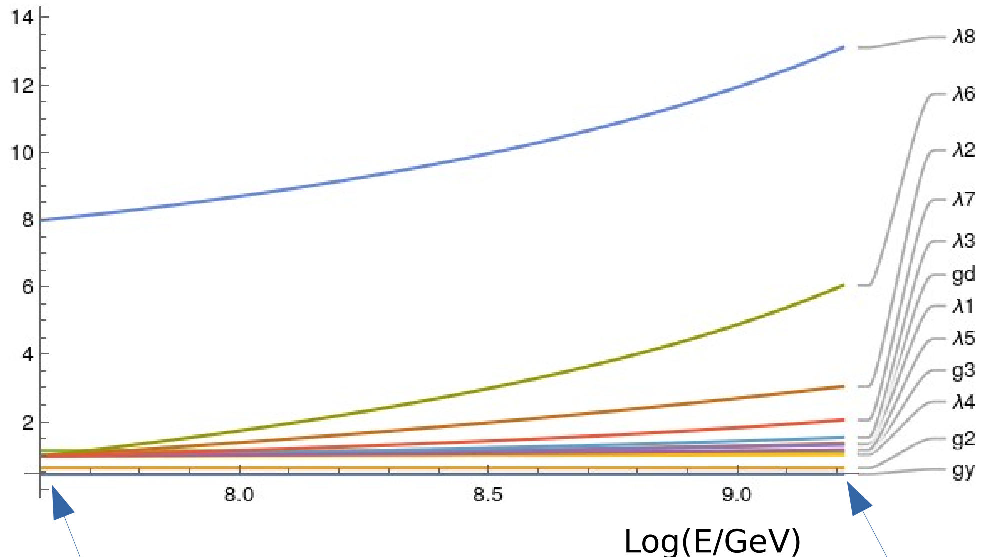
Type-II next-to-2HDM



2 TeV	10 TeV
$\lambda_1(2\,\mathrm{TeV}) = 1$	$\lambda_1(10\,\mathrm{TeV}) = 1.49$
$\lambda_2(2\,\mathrm{TeV}) = 1$	$\lambda_2(10\,\mathrm{TeV}) = 3.84$
$\lambda_3(2\,\mathrm{TeV}) = 1$	$\lambda_3(10\,\mathrm{TeV}) = 1.83$
$\lambda_4(2\,\mathrm{TeV}) = 1$	$\lambda_4(10\,\mathrm{TeV}) = 1.06$
$\lambda_5(2\,\mathrm{TeV}) = 1$	$\lambda_5(10\,\mathrm{TeV}) = 1.28$
$\lambda_6(2\,\mathrm{TeV}) = 1$	$\lambda_6(10\,\mathrm{TeV}) = 9.49$
$\lambda_7(2\,\mathrm{TeV}) = 1$	$\lambda_7(10\,\mathrm{TeV}) = 2.68$
$\lambda_8(2\,\mathrm{TeV}) = 8$	$\lambda_8(10\,\mathrm{TeV}) = 16.43$

daniele.rizzo@ncbj.gov.pl
Daniele Rizzo

Type-II next-to-2HDM



2 TeV

10 TeV

$\lambda_1(2\,\mathrm{TeV}) = 1$ → $\lambda_1(10\,\mathrm{TeV}) = 1.49$

$\lambda_2(2\,\mathrm{TeV}) = 1$ → $\lambda_2(10\,\mathrm{TeV}) = 3.84$

$\lambda_3(2\,\mathrm{TeV}) = 1$ → $\lambda_3(10\,\mathrm{TeV}) = 1.83$

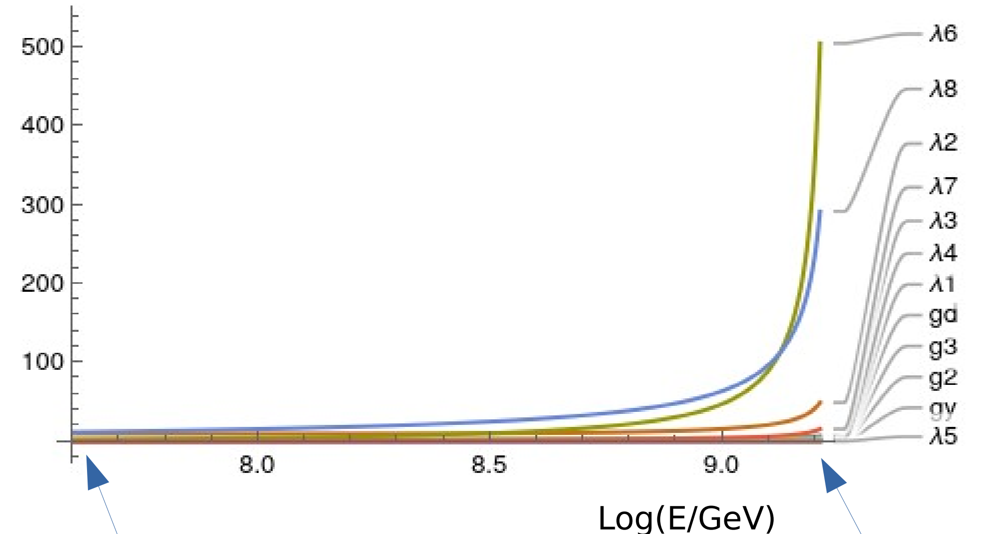
$\lambda_4(2\,\mathrm{TeV}) = 1$ → $\lambda_4(10\,\mathrm{TeV}) = 1.06$

$\lambda_5(2\,\mathrm{TeV}) = 1$ → $\lambda_5(10\,\mathrm{TeV}) = 1.28$

$\lambda_6(2\,\mathrm{TeV}) = 1$ → $\lambda_6(10\,\mathrm{TeV}) = 9.49$

$\lambda_7(2\,\mathrm{TeV}) = 1$ → $\lambda_7(10\,\mathrm{TeV}) = 2.68$

$\lambda_8(2\,\mathrm{TeV}) = 8$ → $\lambda_8(10\,\mathrm{TeV}) = 16.43$



2 TeV

10 TeV

$\lambda_1(2\,\mathrm{TeV}) = 0.26$

$\lambda_2(2\,\mathrm{TeV}) = 9.99$

$\lambda_3(2\,\mathrm{TeV}) = 1.89$

$\lambda_4(2\,\mathrm{TeV}) = 2.04$

$\lambda_5(2\,\mathrm{TeV}) = 0.077$

$\lambda_6(2\,\mathrm{TeV}) = 2.11$

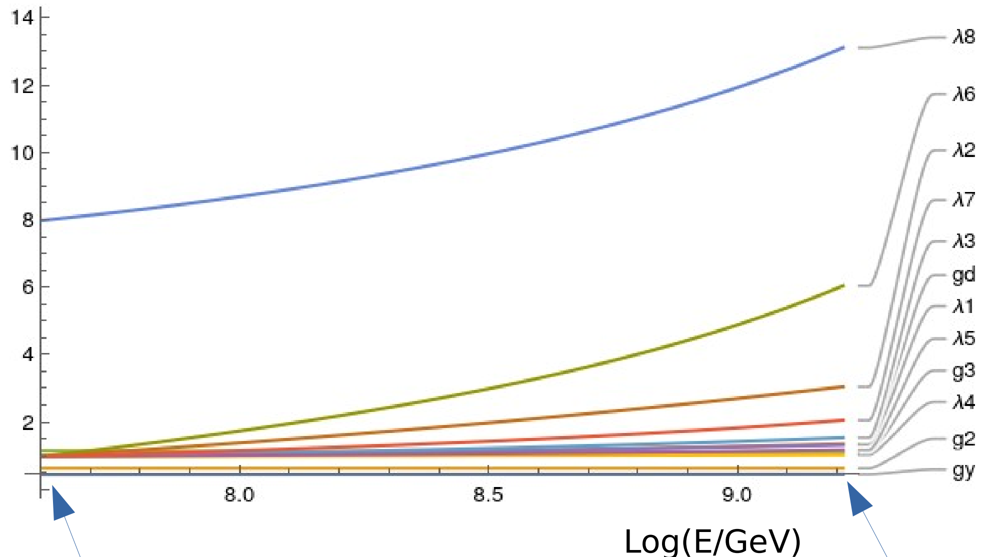
$\lambda_7(2\,\mathrm{TeV}) = 0.00077$

$\lambda_8(2\,\mathrm{TeV}) = 11.77$

daniele.rizzo@ncbj.gov.pl

Daniele Rizzo

Type-II next-to-2HDM



$\lambda_1(2\,\mathrm{TeV}) = 1$ → $\lambda_1(10\,\mathrm{TeV}) = 1.49$

$\lambda_2(2\,\mathrm{TeV}) = 1$ → $\lambda_2(10\,\mathrm{TeV}) = 3.84$

$\lambda_3(2\,\mathrm{TeV}) = 1$ → $\lambda_3(10\,\mathrm{TeV}) = 1.83$

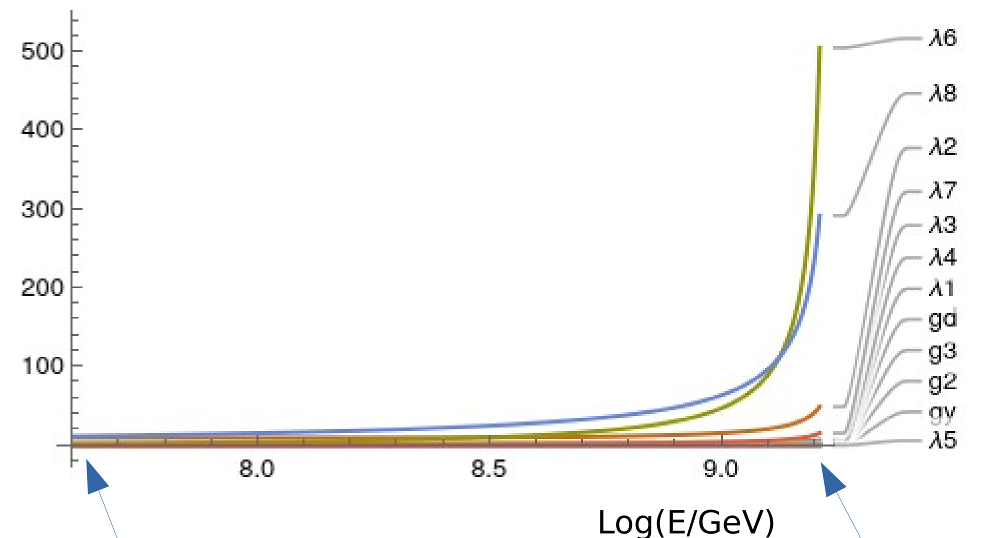
$\lambda_4(2\,\mathrm{TeV}) = 1$ → $\lambda_4(10\,\mathrm{TeV}) = 1.06$

$\lambda_5(2\,\mathrm{TeV}) = 1$ → $\lambda_5(10\,\mathrm{TeV}) = 1.28$

$\lambda_6(2\,\mathrm{TeV}) = 1$ → $\lambda_6(10\,\mathrm{TeV}) = 9.49$

$\lambda_7(2\,\mathrm{TeV}) = 1$ → $\lambda_7(10\,\mathrm{TeV}) = 2.68$

$\lambda_8(2\,\mathrm{TeV}) = 8$ → $\lambda_8(10\,\mathrm{TeV}) = 16.43$



$\lambda_1(2\,\mathrm{TeV}) = 0.26$ → $\lambda_1(10\,\mathrm{TeV}) = 1.45$

$\lambda_2(2\,\mathrm{TeV}) = 9.99$ → $\lambda_2(10\,\mathrm{TeV}) = 49.47$

$\lambda_3(2\,\mathrm{TeV}) = 1.89$ → $\lambda_3(10\,\mathrm{TeV}) = 7.28$

$\lambda_4(2\,\mathrm{TeV}) = 2.04$ → $\lambda_4(10\,\mathrm{TeV}) = 2.42$

$\lambda_5(2\,\mathrm{TeV}) = 0.077$ → $\lambda_5(10\,\mathrm{TeV}) = 0.21$

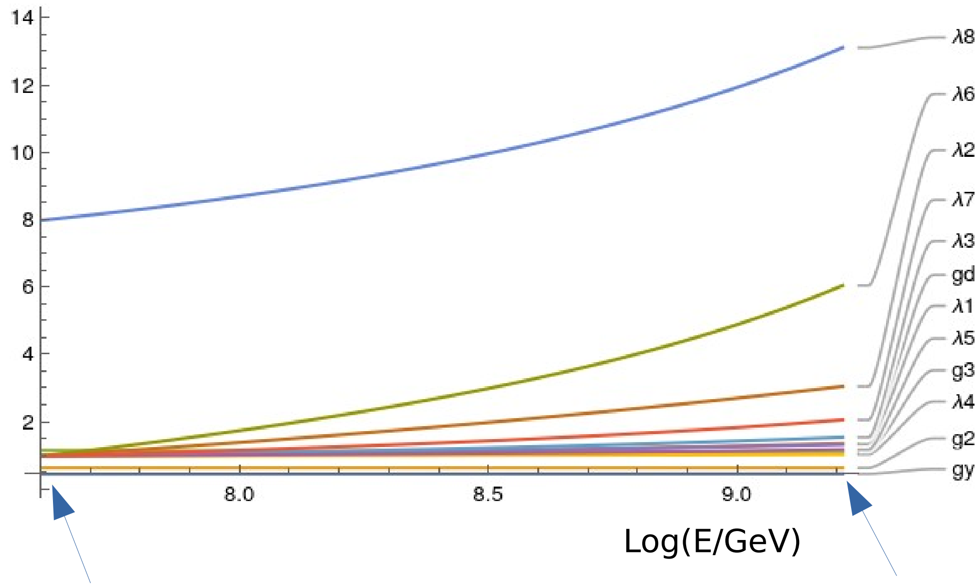
$\lambda_6(2\,\mathrm{TeV}) = 2.11$ → $\lambda_6(10\,\mathrm{TeV}) = 505.12$

$\lambda_7(2\,\mathrm{TeV}) = 0.00077$ → $\lambda_7(10\,\mathrm{TeV}) = 15.65$

$\lambda_8(2\,\mathrm{TeV}) = 11.77$ → $\lambda_8(10\,\mathrm{TeV}) = 291.97$

daniele.rizzo@ncbj.gov.pl
Daniele Rizzo

Type-II next-to-2HDM



$\lambda_1(2\,\mathrm{TeV}) = 1$ → $\lambda_1(10\,\mathrm{TeV}) = 1.49$

$\lambda_2(2\,\mathrm{TeV}) = 1$ → $\lambda_2(10\,\mathrm{TeV}) = 3.84$

$\lambda_3(2\,\mathrm{TeV}) = 1$ → $\lambda_3(10\,\mathrm{TeV}) = 1.83$

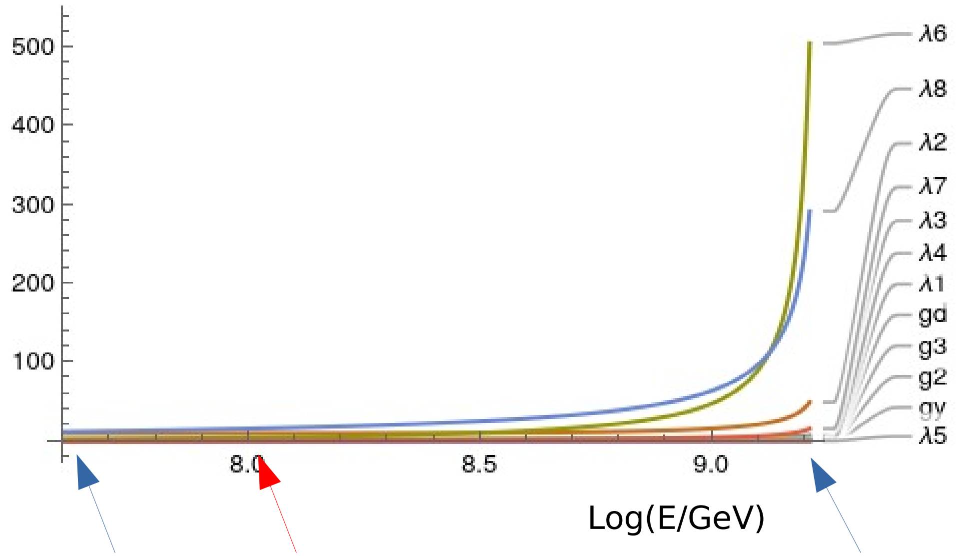
$\lambda_4(2\,\mathrm{TeV}) = 1$ → $\lambda_4(10\,\mathrm{TeV}) = 1.06$

$\lambda_5(2\,\mathrm{TeV}) = 1$ → $\lambda_5(10\,\mathrm{TeV}) = 1.28$

$\lambda_6(2\,\mathrm{TeV}) = 1$ → $\lambda_6(10\,\mathrm{TeV}) = 9.49$

$\lambda_7(2\,\mathrm{TeV}) = 1$ → $\lambda_7(10\,\mathrm{TeV}) = 2.68$

$\lambda_8(2\,\mathrm{TeV}) = 8$ → $\lambda_8(10\,\mathrm{TeV}) = 16.43$



$\lambda_1(2\,\mathrm{TeV}) = 0.26$ → $\lambda_1(10\,\mathrm{TeV}) = 1.45$

$\lambda_2(2\,\mathrm{TeV}) = 9.99$ → $\lambda_2(10\,\mathrm{TeV}) = 49.47$

$\lambda_3(2\,\mathrm{TeV}) = 1.89$ → $\lambda_3(10\,\mathrm{TeV}) = 7.28$

$\lambda_4(2\,\mathrm{TeV}) = 2.04$ → $\lambda_4(10\,\mathrm{TeV}) = 2.42$

$\lambda_5(2\,\mathrm{TeV}) = 0.077$ → $\lambda_5(10\,\mathrm{TeV}) = 0.21$

$\lambda_6(2\,\mathrm{TeV}) = 2.11$ → $\lambda_6(10\,\mathrm{TeV}) = 505.12$

$\lambda_7(2\,\mathrm{TeV}) = 0.00077$ → $\lambda_7(10\,\mathrm{TeV}) = 15.65$

$\lambda_8(2\,\mathrm{TeV}) = 11.77$ → $\lambda_8(10\,\mathrm{TeV}) = 291.97$

daniele.rizzo@ncbj.gov.pl Daniele Rizzo

Type-II next-to-2HDM

Work in progress:

- Perform the minimization of the loss-function with multi-core random walk to find the parameters for the models.
- Perform the same minimization with genetic algorithm, gradient descent and other machine learning techniques.
- Perform the analysis of already existing bounds from LHC for the production of the scalar particles, the VL-fermions and (in the local model) of the Z'.

Ideas for a next project:

- Study the quark sector of the model by taking into account new observable than can set constraints on their parameter space.
- Repeat the entire analysis by adding a second family of VL-fermions, so that we can also generate a mass for the first generation of leptons.
- ...

Hoping you are still awake

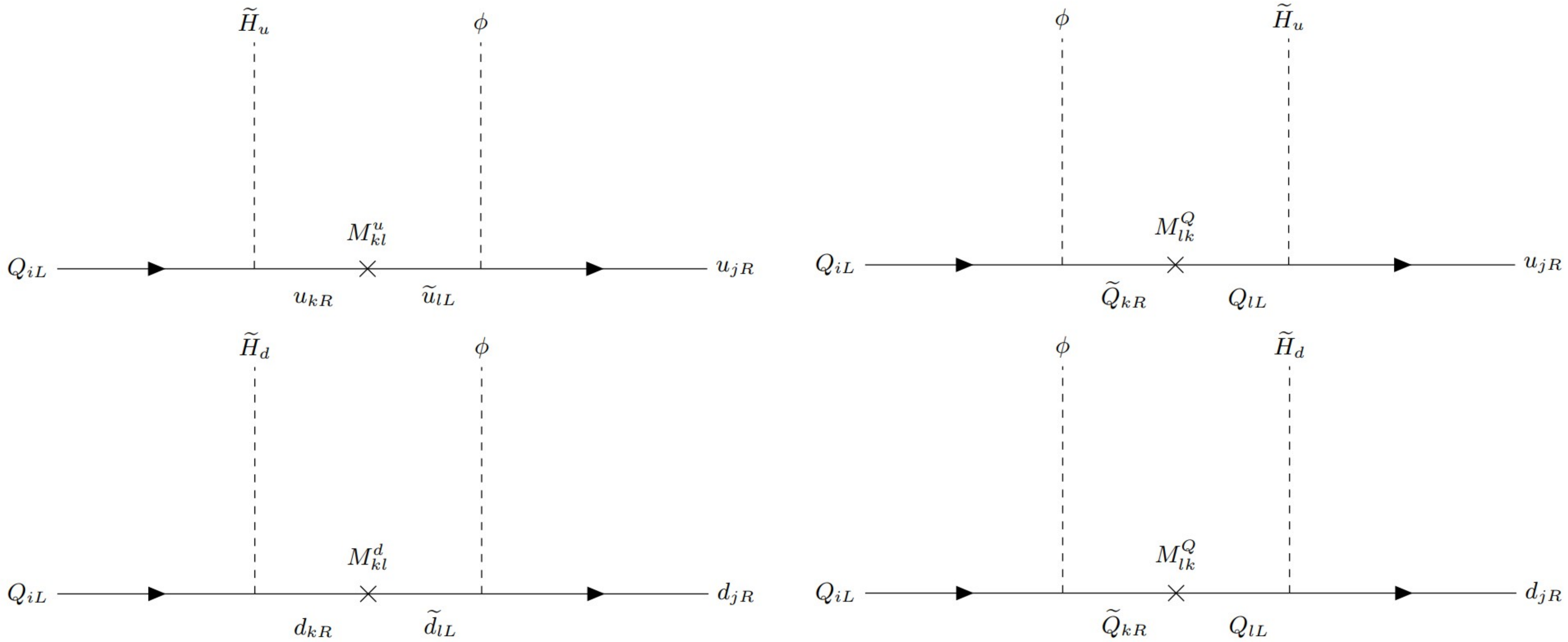
Thanks for the attention!

daniele.rizzo@ncbj.gov.pl

Daniele Rizzo

Type-II next-to-2HDM

$$
\begin{aligned}
\mathcal{L}_q^{\text{Yukawa+Mass}} &= y^u_{ik}\overline{Q}_{iL}\widetilde{H}_u u_{kR} + x^u_{ki}\phi\overline{\widetilde{u}}_{kL}u_{iR} + x^Q_{ik}\phi\overline{Q}_{iL}\widetilde{Q}_{kR} + y^u_{ki}\overline{Q}_{kL}\widetilde{H}_u u_{iR} \\
&+ y^d_{ik}\overline{Q}_{iL}\widetilde{H}_d d_{kR} + x^d_{ki}\phi\overline{\widetilde{d}}_{kL}d_{iR} + y^d_{ki}\overline{Q}_{kL}\widetilde{H}_d d_{iR} \\
&+ M^u_{kl}\overline{\widetilde{u}}_{lL}u_{kR} + M^d_{kl}\overline{\widetilde{d}}_{lL}d_{kR} + M^Q_{kl}\overline{Q}_{kL}\widetilde{Q}_{lR} + \text{h. c.}
\end{aligned}
$$

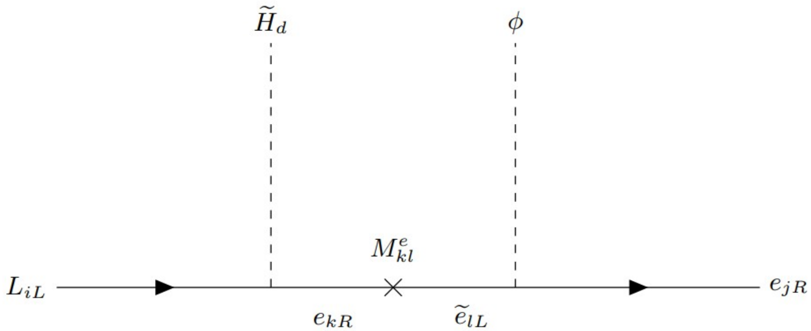


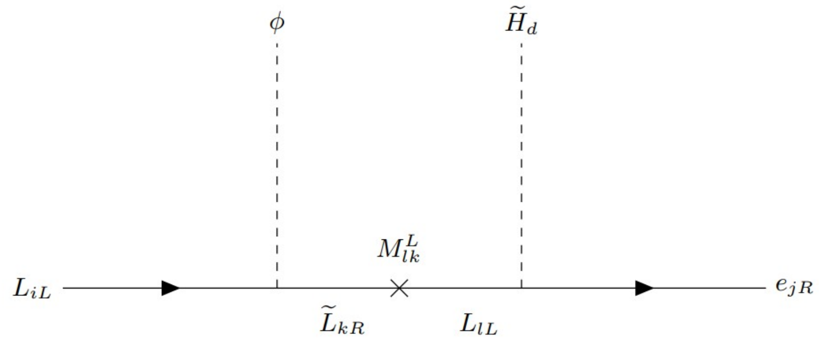
daniele.rizzo@ncbj.gov.pl
Daniele Rizzo

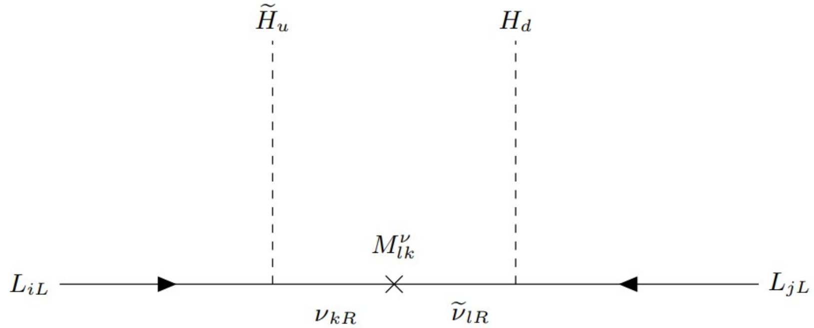
Type-II next-to-2HDM

$$\mathcal{L}_e^{\text{Yukawa+Mass}} = y^e_{ik}\overline{L}_{iL}\widetilde{H}_d e_{kR} + x^e_{ki}\phi\overline{\widetilde{e}}_{kL}e_{iR} + x^L_{ik}\phi\overline{L}_{iL}\widetilde{L}_{kR} + y^e_{ki}\overline{L}_{kL}\widetilde{H}_d e_{iR}$$
$$+ M^e_{kl}\overline{\widetilde{e}}_{lL}e_{kR} + M^L_{kl}\overline{L}_{kL}\widetilde{L}_{lR} + \text{h. c.},$$

$$\mathcal{L}_\nu^{\text{Yukawa+Mass}} = y^\nu_{ik}\overline{L}_{iL}\widetilde{H}_u\nu_{kR} + x^L_{ik}\overline{L}_{iL}H_d\overline{\widetilde{\nu}}_{kR} + M^M_{kl}\overline{\widetilde{\nu}}_{lR}\nu_{kR} + \text{h. c.}$$







daniele.rizzo@ncbj.gov.pl
Daniele Rizzo

Type-II next-to-2HDM

$$\mathcal{L}_e^{\text{Yukawa+Mass}} = y_{ik}^e \overline{L}_{iL} \widetilde{H}_d e_{kR} + x_{ki}^e \phi \overline{\widetilde{e}}_{kL} e_{iR} + x_{ik}^L \phi \overline{L}_{iL} \widetilde{L}_{kR} + y_{ki}^e \overline{L}_{kL} \widetilde{H}_d e_{iR} + M_{kl}^e \overline{\widetilde{e}}_{lL} e_{kR} + M_{kl}^L \overline{L}_{kL} \widetilde{L}_{lR} + \text{h. c.},$$

$$M^\psi = \left(\begin{array}{c|ccccc} & \psi_{1R} & \psi_{2R} & \psi_{3R} & \psi_{4R} & \widetilde{\psi}_{4R} \\ \hline \overline{\psi}_{1L} & 0 & 0 & 0 & y_{14}^\psi \langle \widetilde{H}^0 \rangle & x_{14}^\psi \langle \phi \rangle \\ \overline{\psi}_{2L} & 0 & 0 & 0 & y_{24}^\psi \langle \widetilde{H}^0 \rangle & x_{24}^\psi \langle \phi \rangle \\ \overline{\psi}_{3L} & 0 & 0 & 0 & y_{34}^\psi \langle \widetilde{H}^0 \rangle & x_{34}^\psi \langle \phi \rangle \\ \overline{\psi}_{4L} & y_{41}^\psi \langle \widetilde{H}^0 \rangle & y_{42}^\psi \langle \widetilde{H}^0 \rangle & y_{43}^\psi \langle \widetilde{H}^0 \rangle & 0 & M_{44}^\psi \\ \overline{\widetilde{\psi}}_{4L} & x_{41}^{\psi'} \langle \phi \rangle & x_{42}^{\psi'} \langle \phi \rangle & x_{43}^{\psi'} \langle \phi \rangle & M_{44}^{\psi'} & 0 \end{array} \right)$$

daniele.rizzo@ncbj.gov.pl

Daniele Rizzo

Type-II next-to-2HDM

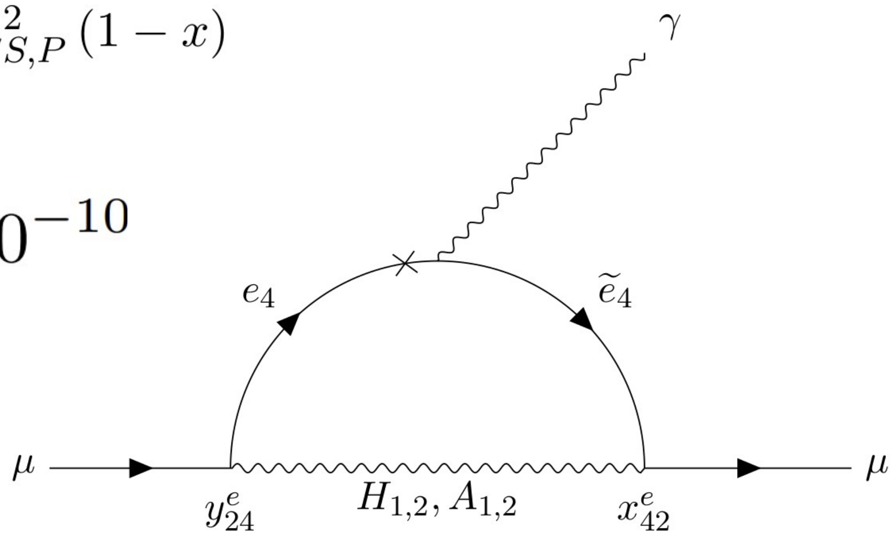
Analytical expression for the muonic g-2

$$\Delta a_\mu = \frac{y_{24}^2}{\sqrt{2}} \frac{x_{42}^e}{\sqrt{2}} \frac{m_\mu^2}{8\pi} \Big[(R_e^T)_{22} (R_e^T)_{32} I_S^\mu \left(M_{\widetilde{E}_4}, m_{H_1} \right) + (R_e^T)_{23} (R_e^T)_{33} I_S^\mu \left(M_{\widetilde{E}_4}, m_{H_2} \right)$$
$$+ (R_o^T)_{22} (R_o^T)_{32} I_P^\mu \left(M_{\widetilde{E}_4}, m_{A_1} \right) + (R_o^T)_{23} (R_o^T)_{33} I_P^\mu \left(M_{\widetilde{E}_4}, m_{A_2} \right) \Big]$$

$$I_{S,P}^\mu \left(M_{\widetilde{E}_4}, m_H \right) = \int_0^1 dx \frac{x^2 \left(1 - x \pm \frac{M_{\widetilde{E}_4}}{m_\mu} \right)}{m_\mu^2 x^2 + \left(M_{\widetilde{E}_4}^2 - m_\mu^2 \right) x + m_{S,P}^2 (1-x)}$$

$$\Delta a_\mu = a_\mu^{\mathrm{Exp}} - a_\mu^{\mathrm{SM}} = (26.1 \pm 8.0) \times 10^{-10}$$

Put here the value from best-fit xi^2



daniele.rizzo@ncbj.gov.pl
Daniele Rizzo

Phenomenological problems of The Standard Model

W mass anomaly

$$0.0496 < \Delta M_W < 0.0624$$

Put here M_W from best-fit xi^2

$$\Delta S = 0.06 \pm 0.10.$$

$$\Delta T = 0.11 \pm 0.12.$$

Put here S T U from best-fit xi^2

$$\Delta U = 0.13 \pm 0.09$$

daniele.rizzo@ncbj.gov.pl

Daniele Rizzo