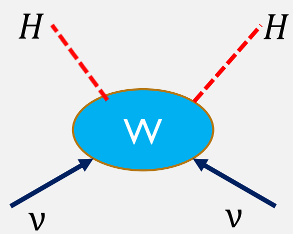
MILLENNIUM INSTITUTE FOR SUBATOMIC PHYSICS AT HIGH-ENERGY FRONTIER SAPHIR

Neutrino Mass and Chiral Symmetry Breaking

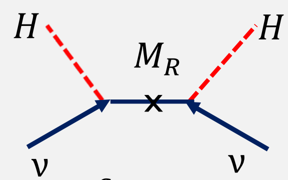
A. Babic, S. Kovalenko, M. Krivoruchenko, F. Simkovic

Neutrino mass models



$$O_W \sim \frac{1}{\Lambda} L\, H \cdot LH$$

High-scale Seesaw I

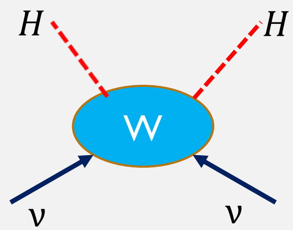


$\nu^C(1,1,;0)$

$$m_\nu \sim m_D\, M_R^{-1}\, m_D$$

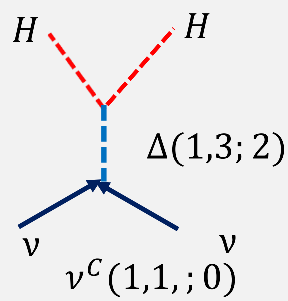
$M_R \sim 10^{12}$ GeV

Neutrino mass models



$$O_W \sim \frac{1}{\Lambda} L\,H \cdot LH$$

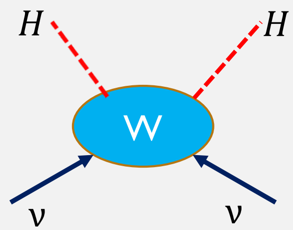
High-scale Seesaw II



$$m_\nu \sim \frac{\langle H \rangle^2}{M_\Delta^2}\mu$$

$M_R \sim 10^{12}$ GeV

Neutrino mass models



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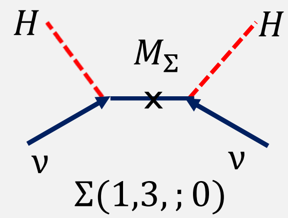
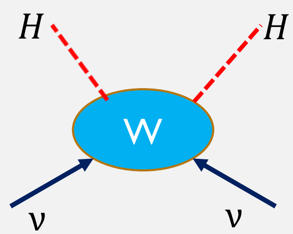
High-scale Seesaw III



$$m_\nu \sim m_D\, M_\Sigma^{-1}\, m_D$$

$$M_\Sigma \sim 10^{12}\ \text{GeV}$$

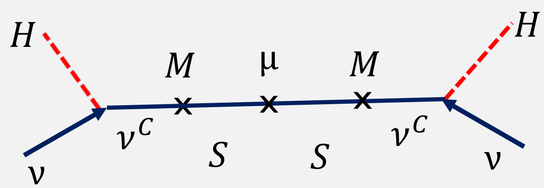
Neutrino mass models



$$O_W \sim \frac{1}{\Lambda} L\,H \cdot LH$$

Low-scale Seesaw

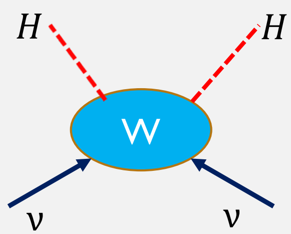
Inverse Seesaw



$$m_\nu \sim m_D (M^T)^{-1}\ \mu\ \ M^{-1}\, m_D$$

The TeV scale masses for sufficiently small μ

Neutrino mass models



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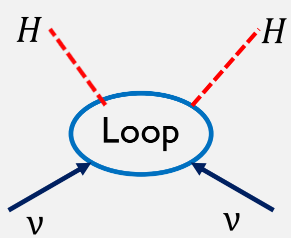
Low-scale Seesaw



Loop Seesaw

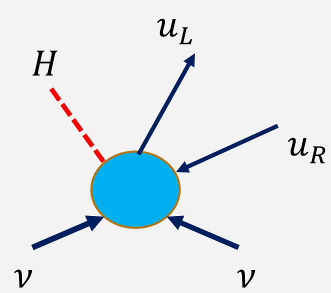
Internal particle masses in the TeV ballpark

Neutrino Mass and Chiral Symmetry Breaking

$$O_7 = \frac{g_{\alpha\beta}}{\Lambda^3}\ \overline{L^C_\alpha}\, L_\beta\, H\, (\overline{Q}\, u_R)$$

Neutrino Mass and Chiral Symmetry Breaking

$$O_7 = \frac{g_{\alpha\beta}}{\Lambda^3}\ \overline{\nu_\alpha^C}\,\nu_\beta\, H\,(\overline{u_L}\,u_R) + \ldots.$$



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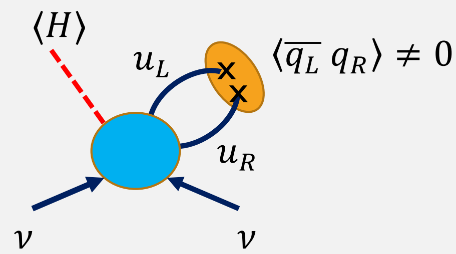

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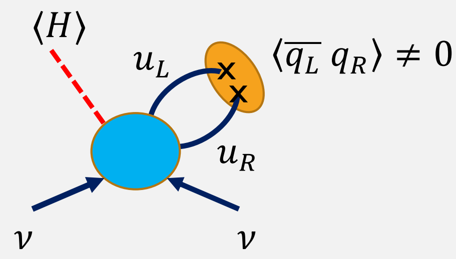

$$m_\nu \sim \langle H\rangle\,\frac{\langle\overline{q_L}\,q_R\rangle}{\Lambda^3}$$

Neutrino Mass and Chiral Symmetry Breaking

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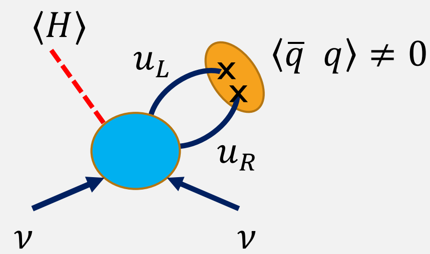

$$m_\nu \sim \langle H \rangle \frac{\langle \bar{q}\, q \rangle}{\Lambda^3}$$

$\langle \overline{u_L}\, u_R \rangle \approx -(287\ MeV)^3$ Light meson phenomenology

$\Lambda \sim 1$ TeV

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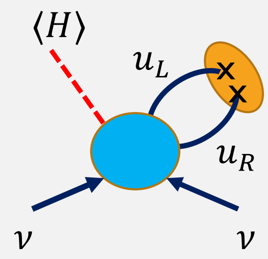

$$m_\nu \sim \langle H \rangle \frac{\langle \bar{q}\, q \rangle}{\Lambda^3} \sim 1 \text{ eV}$$

$$\langle \overline{u_L}\, u_R \rangle \approx -(287\ MeV)^3$$ Light meson phenomenology

$\Lambda \sim 1$ TeV

Neutrino Mass and Chiral Symmetry Breaking

$$O_W = \frac{g^W_{\alpha\beta}}{\Lambda}\ \overline{L^C_\alpha}\, L_\beta\, H\, H$$

?

Phenomenological relevance of $O_7 = \frac{g_{\alpha\beta}}{\Lambda^3}\ \overline{L^C_\alpha}\, L_\beta\, H\, (\overline{Q}\, u_R)$

Neutrino Mass and Chiral Symmetry Breaking

$$O_W = \frac{g^W_{\alpha\beta}}{\Lambda} \; \overline{L^C_\alpha} \, L_\beta \, H \, H \qquad ?$$

$$O_7 = \frac{g_{\alpha\beta}}{\Lambda^3} \; \overline{L^C_\alpha} \, L_\beta \, H \, (\bar{Q} \, u_R)$$

Symmetry **G** forbidding O_W while allowing O_7

Properties:

- H is **G**-singlet ⇒ G-symmetry is unbroken down to the chiral symmetry breaking scale
- $(\overline{L^C} \, L)$ is **G**-non-singlet
- $(\bar{Q} \, u_R)$ is **G**-non-singlet

Neutrino Mass and Chiral Symmetry Breaking

$$O_7 = \frac{g_{\alpha\beta}}{\Lambda^3} \; \overline{L_\alpha^C} \, L_\beta \, H \, (\bar{Q} \, u_R)$$

Symmetry **G** forbidding O_W

$H \, (\bar{Q} \, u_R)$ is also forbidden by **G**

$\Downarrow$

$m_u = 0$

Neutrino Mass and Chiral Symmetry Breaking

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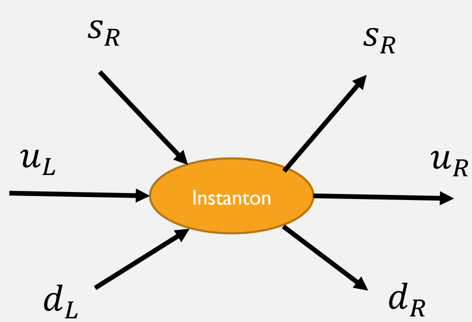
$m_u = 0$ **!**

$m_u^{latt} = 2.78 \pm 0.19$ MeV

and Gell-Mann–Oakes–Renner relation for pion masses requiring $m_{u,d} \neq 0$

‘t Hooft instanton vertex



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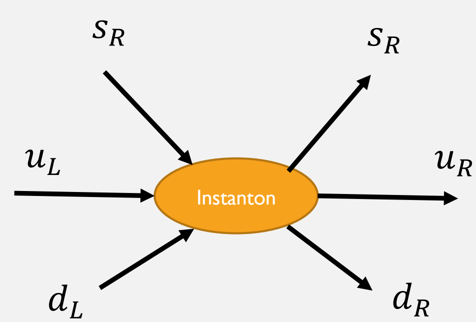
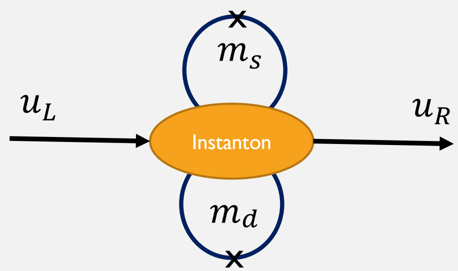


$m_d \neq 0,\ m_s \neq 0$

‘t Hooft instanton vertex



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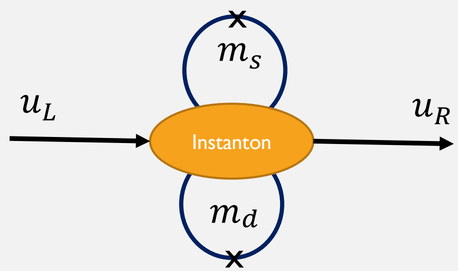

$$m_u^{inst} = 2.33 \pm 0.20 \ \ \text{MeV}$$

[N. Kitazawa and Y. Sakai, Int. J. Mod. Phys. A 33, 1850017 (2018)]

Neutrino Mass and Chiral Symmetry Breaking

$$O_7 = \frac{g_{\alpha\beta}}{\Lambda^3}\ \overline{L_\alpha^C}\, L_\beta\, H\, (\bar{Q}\, u_R)$$

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$$m_u = 0$$

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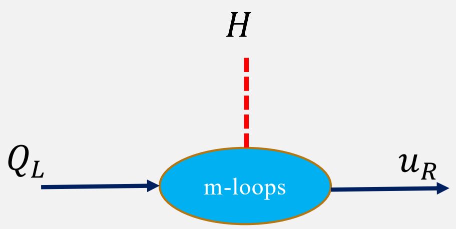
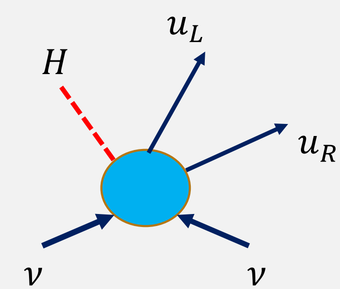
Way out: QCD instanton $m_u^{inst} = 2.33 \pm 0.20$ MeV

Neutrino Mass and Chiral Symmetry Breaking

Softly-broken O7-protecting symmetry **G**



$$H\,(\bar{Q}\,u_R)$$



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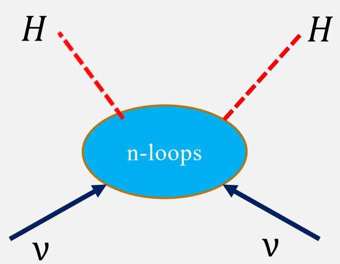

$$O_W = \frac{g^W_{\alpha\beta}}{\Lambda}\ \overline{L_\alpha^C}\,L_\beta\,H\,H$$

Neutrino Mass and Chiral Symmetry Breaking

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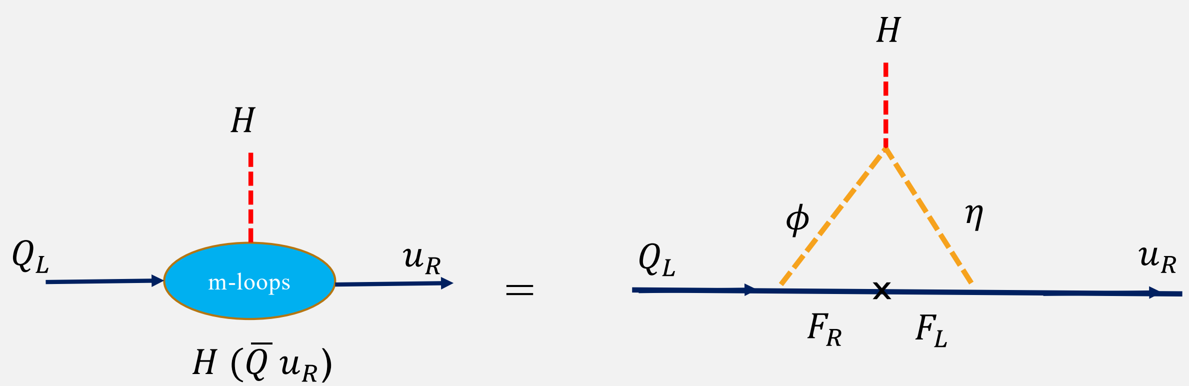
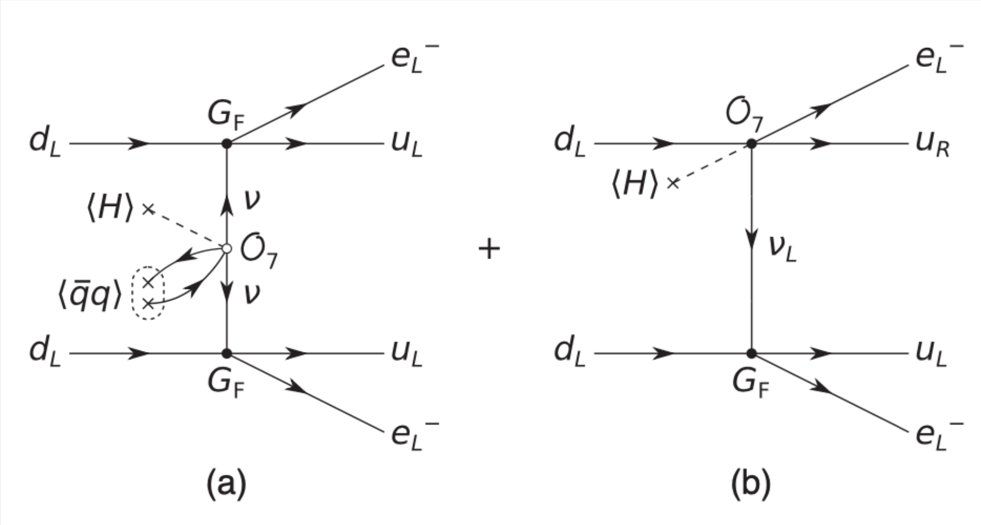


$F_{L,R}\ (1,6;0)$ $\quad \phi(1,5;1/3)$ $\quad \eta(1,6;4/3)$

Neutrino Mass and Chiral Symmetry Breaking

$$O_7 = \frac{g_{\alpha\beta}}{\Lambda^3}\ \overline{L^C_\alpha}\, L_\beta\, H\, (\bar{Q}\, u_R)$$

Phenomenology



$0\nu\beta\beta - Decay$

Applying combined analysis of neutrino oscillation data and $0\nu\beta\beta - Decay$ half-life lower limit

Model predicts: **Normal Ordering** of neutrino masses with

2.65 meV $\leq m_0 = m_1 \leq 6.84$ meV

9.0 meV $\leq m_2 \leq 11.2$ meV

49.8 meV $\leq m_3 \leq 50.8$ meV

CONCLUSIONS

- Small neutrino mass induced by a combined effect of the Chiral Symmetry breaking and Tev scale-BSM physics

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Thank you !

BSM models

Neutrino Mass and Chiral Symmetry Breaking

QCD Lagrangian: $\mathcal{L} = \overline{q}_{\mathrm{L}}\, i\not{D}\, q_{\mathrm{L}} + \overline{q}_{\mathrm{R}}\, i\not{D}\, q_{\mathrm{R}} + \mathcal{L}_{\mathrm{gluons}}$ $\quad q = \begin{bmatrix} u \\ d \end{bmatrix}$

Chiral symmetry: $SU(2)_L \times SU(2)_R$

$$q_{L,R} = U_{L,R}\, q_{L,R}$$

There is no explicit Ch symmetry of the hadronic spectrum

Ch symmetry must be broken spontaneously

Chiral Symmetry

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Chiral symmetry: $SU(2)_{\mathrm{L}} \times SU(2)_{\mathrm{R}} \times U(1)_V \times U(1)_A$

$$q_{L,R} = U_{L,R}\, q_{L,R} \qquad q_{L,R} = e^{i\theta_V} \mathrm{q}_{L,R} \qquad q_{L/R} = e^{\pm i\theta_A} \mathrm{q}_{L/R}$$

Non-perturbative QCD effects Quark condensate $\langle \overline{q_L} q_R \rangle \neq 0$

Spontaneous Breaking of Chiral symmetry $SU(2)_L \times SU(2)_R \xrightarrow{\langle \overline{q_L}\, q_R \rangle} SU(2)_I$ 3 Goldstones: $\pi^{\pm}, \pi^0$

Soft breaking of Ch Symmetry: $m_q\, \overline{q_L} q_R$ current quark masses 3 Pseudo-Goldstones:

BSM models

Neutrino Mass and Chiral Symmetry Breaking

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