A new solution to the Strong CP problem and the neutrino masses

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Work in Collaboration with
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arXiv: 1904.05360

Motivation

- The success of SM relies on few principles:

  ▷ Lorentz invariance

  ▷ Gauge-invariance

  ▷ Renormalizability

- Naturally leads to:

  ▷ Accidental flavour symmetries in the gauge sector

  $$U(3)^5 = SU(3)^5 \times U(1)_B \times U(1)_L \times U(1)_Y \times U(1)_{PQ} \times U(1)_{e_R}$$

  ▷ Absence of FCNC at tree-level

  ▷ GIM suppression at loop level

Motivation

- However the same procedure leads to

  - O(1) CP-violating in the QCD (Strong CP)

  - Instability of Higgs mass (Hierarchy)

- Other issues:

  - Smallness of the neutrino masses:

    $$m_\nu \sim 10^{-2} - 10^{-4}\,\mathrm{eV}$$
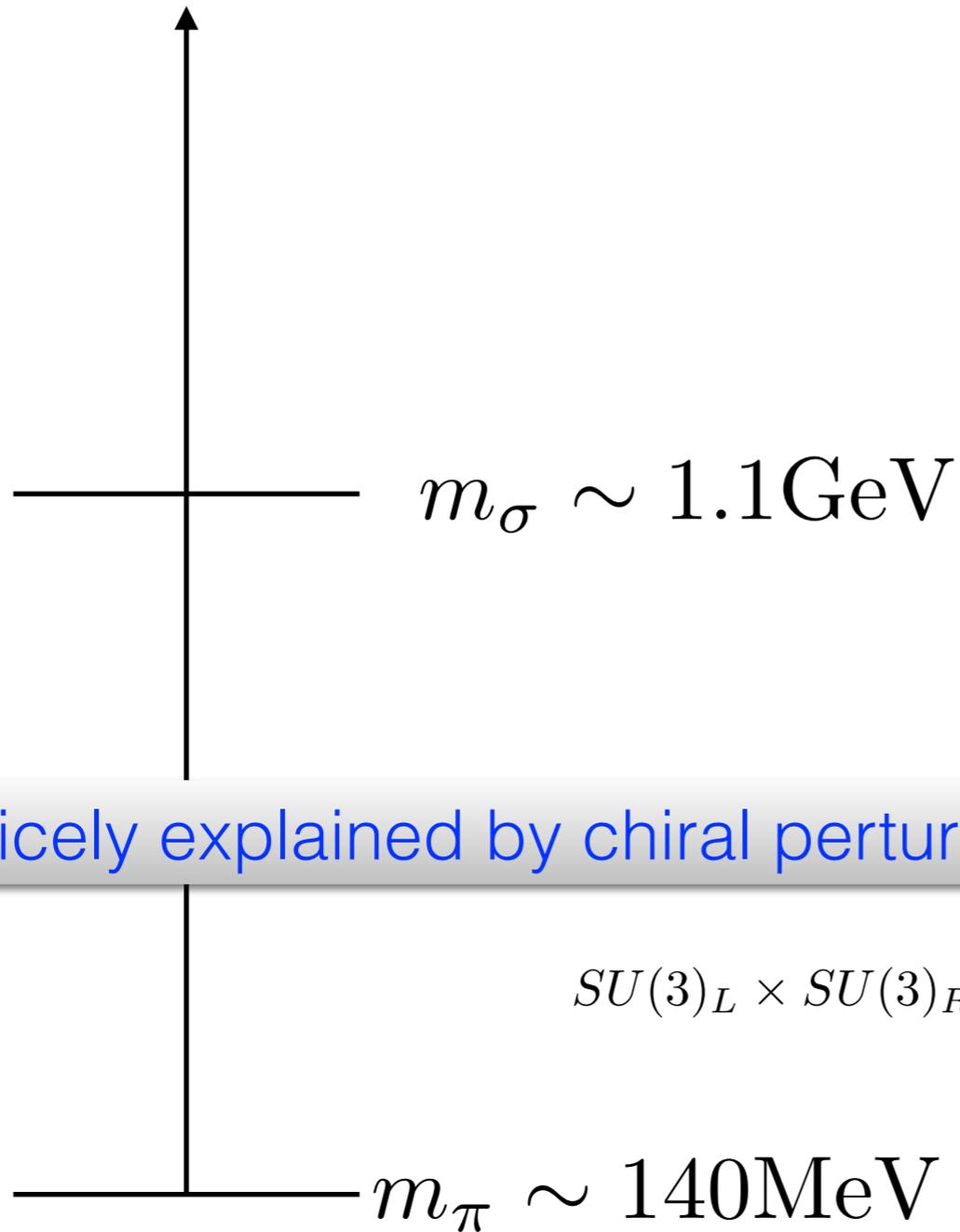
  - Lack of Dark Matter candidate

Motivation

- However the same procedure leads to

  ▷ O(1) CP-violating in the QCD (Strong CP)

  ▷ Instability of Higgs mass (Hierarchy)

  Focus of this talk

- Other issues:

  ▷ Smallness of the neutrino masses:

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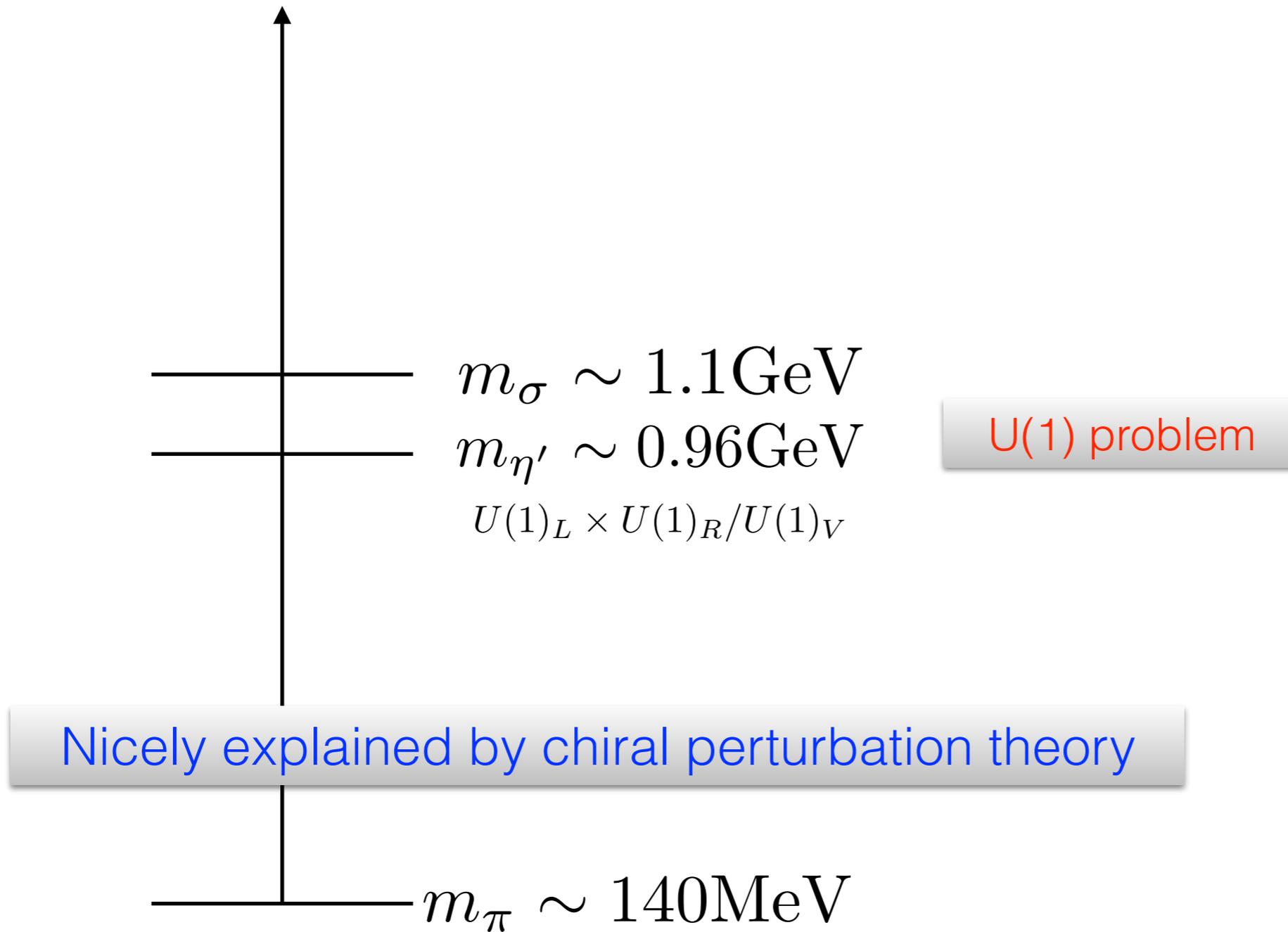
  ▷ Lack of Dark Matter candidate

θ term in QCD

$$\mathcal{L} = -\frac{\theta g_s^2}{32\pi^2} G_{\mu\nu}^a \tilde{G}^{a\mu\nu}$$

- Allowed by gauge invariance, Lorentz invariance and Renormalizablility

- Given the O(1) CP-violating phase in CKM matrices, θ is expected to be O(1)

- Total derivative at classical level, relevant at quantum

The relevance of θ in QCD

$m_\sigma \sim 1.1\text{GeV}$

Nicely explained by chiral perturbation theory

$SU(3)_L \times SU(3)_R / SU(3)_V$

$m_\pi \sim 140\text{MeV}$

The relevance of θ in QCD

$m_\sigma \sim 1.1\,\mathrm{GeV}$

$m_{\eta'} \sim 0.96\,\mathrm{GeV}$

$U(1)_L \times U(1)_R / U(1)_V$

U(1) problem

Nicely explained by chiral perturbation theory

$m_\pi \sim 140\,\mathrm{MeV}$
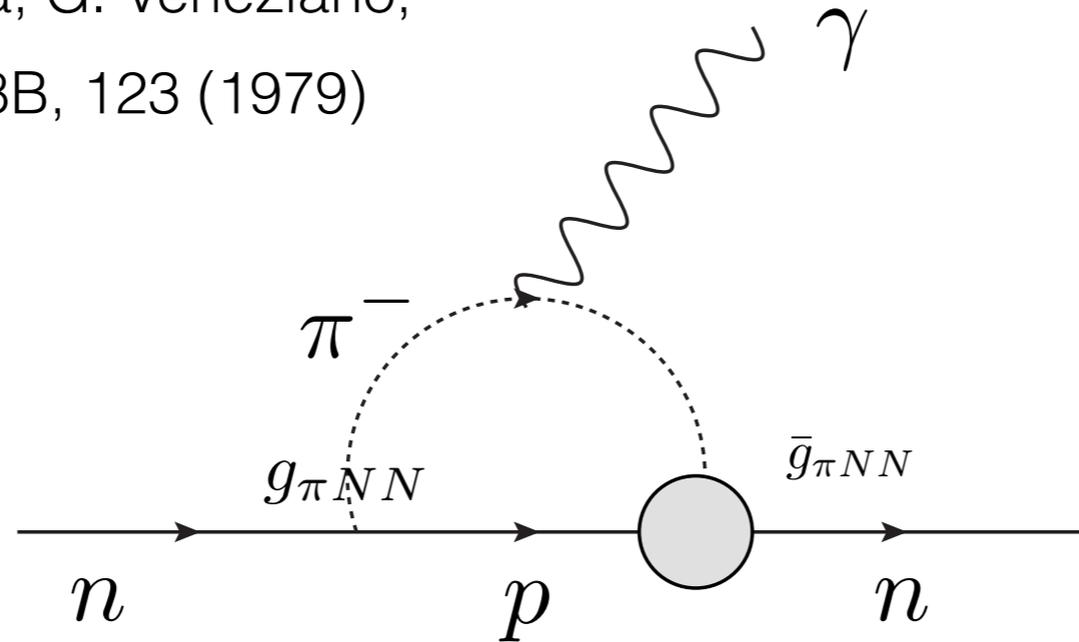
The relevance of θ in QCD

U(1) problem

$$\partial^\mu J_\mu^5 = \frac{g_s^2}{16\pi^2} G_{\mu\nu}^a \tilde{G}^{a\mu\nu}$$

- Total derivative at classical level

- Instanton configuration make it physical

- One instanton configuration $e^{-\frac{8\pi^2}{g_s^2}}$

The relevance of θ in QCD

R. J. Crewther, P. Di Vecchia, G. Veneziano,

and E. Witten, Phys. Lett. 88B, 123 (1979)

$$\frac{d_n}{e} \sim \frac{g_{\pi NN}\,\bar{g}_{\pi NN}}{4\pi^2 M_N}\ln\frac{M_N}{m_\pi}, \qquad \bar{g}_{\pi NN} \sim \theta_{QCD}\frac{m_{eff}}{F_\pi} \qquad m_{eff} \sim \frac{m_u m_d}{m_u + m_d}$$

Similar to QCD sum rules result

$$d_n \sim \theta_{\mathrm{QCD}} \times (2.4 \pm 0.7) \times 10^{-16}\,\mathrm{e\ cm},$$

M. Pospelov and A. Ritz, 9908508

The relevance of θ in QCD

$$\mathcal{L} = -\frac{\theta g_s^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$

- Solution to U(1) problem makes it relevant

- CP-violating effects in QCD: nEDM, $\quad \eta \to \pi\pi$

- $|\theta| < 0.0000000013 \quad (10^{-10})$ Call for an explanation!

J.M. Pendlebury et al., 1509.04411

Solutions to Strong CP

- Make θ dynamical field: axion

  R.D. Peccei and H. R. Quinn
  F. Wilczek
  S. Weinberg

- Make CP exact symmetries and break it spontaneously: Nelson-Barr Mechanism

  A. E. Nelson
  S. M. Barr

- up quark is massless

  H. Georgi and I. N. McArthur
  K. Choi, C.W. Kim and W.K. Sze
  T. Banks, Y. Nir and N. Seiberg
  W. A. Bardeen

  η' is the axion

The role of quark

$$\mathcal{L} = -\frac{\theta g_s^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$

- One flavour QCD

$$u_R \to e^{i\alpha} u_R \qquad\qquad \mathcal{L} \to \alpha \frac{g_s^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$

Only parameter invariant under field redefinition is physical

$$\theta_{\text{QCD}} = \theta + \arg[m_u]$$

- In general $\qquad\qquad \theta_{\text{QCD}} = \theta + \arg[\det M_q]$

Reinterpret the bound

- In a basis $\qquad \theta_{\mathrm{QCD}} = \arg[m_u]$ $\qquad$

$$|m_u|(1\,\mathrm{GeV}) \sim 3\,\mathrm{MeV}$$

$$|\theta_{\mathrm{QCD}}| < 1.3 \times 10^{-10} \Rightarrow \mathrm{Im}[m_u] < 4.0 \times 10^{-4}\mathrm{eV}$$

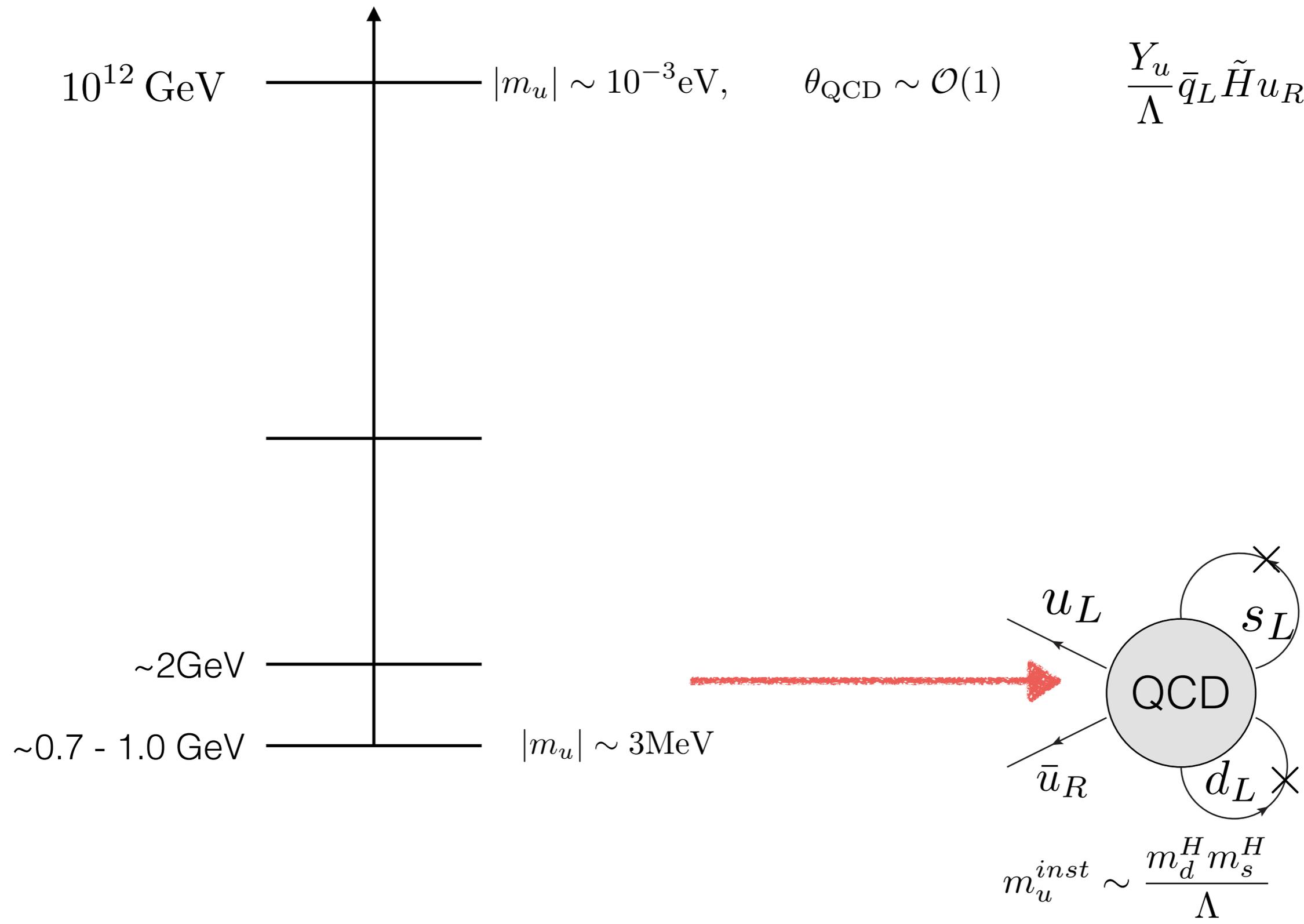- Neutrino mass $\qquad \mathrm{NH} : m_3 \sim 0.05\,\mathrm{eV}, \qquad m_2 \sim 0.0086\,\mathrm{eV}$

Explain the small scale

Tiny up quark mass

$$\theta_{\mathrm{QCD}} = \arg[m_u]$$

$10^{12}\,\mathrm{GeV}$ —— $|m_u| \sim 10^{-3}\mathrm{eV}, \qquad \theta_{\mathrm{QCD}} \sim \mathcal{O}(1)$ $\qquad \dfrac{Y_u}{\Lambda}\bar{q}_L\tilde{H}u_R S$

$\sim 2\mathrm{GeV}$ ——

$\sim 0.7\text{ - }1.0\,\mathrm{GeV}$ —— $|m_u| \sim 3\mathrm{MeV}$

u_L s_L

QCD

$\bar{u}_R$ d_L

$$m_u^{inst} \sim \frac{m_d^H m_s^H}{\Lambda}$$

Tiny up quark mass

$$\theta_{\mathrm{QCD}} = \arg[m_u]$$

$10^{12}\,\mathrm{GeV}$ ———————— $|m_u| \sim 10^{-3}\mathrm{eV}, \qquad \theta_{\mathrm{QCD}} \sim \mathcal{O}(1)$

~2GeV ———————— $\boxed{|m_u| \sim 2\mathrm{MeV}}$ Lattice: A. Bazavov et al.

                                                     S. Aoki et al.

~0.7 - 1.0 GeV ———————— $|m_u| \sim 3\mathrm{MeV}$

Bypass the lattice

$$\theta_{\mathrm{QCD}} = \arg[m_u]$$

$10^{12} \ \mathrm{GeV}$ — $|m_u| \sim 10^{-3}\mathrm{eV}, \qquad \theta_{\mathrm{QCD}} \sim \mathcal{O}(1)$

P. Agrawal and K. Howe, 1712.05803

q_L^1, u_R^c, d_R^c $\qquad\qquad$ q_L^2, c_R^c, s_R^c $\qquad\qquad$ q_L^3, t_R^c, b_R^c

$10^3 \mathrm{TeV}$ — $SU(3)_1$ —— $SU(3)_2$ —— $SU(3)_3$

~2GeV — $\boxed{|m_u| \sim 2\mathrm{MeV}}$ $\qquad$ Lattice: A. Bazavov et al.
$\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad$ S. Aoki et al.

~0.7 - 1.0 GeV — $|m_u| \sim 3\mathrm{MeV}$
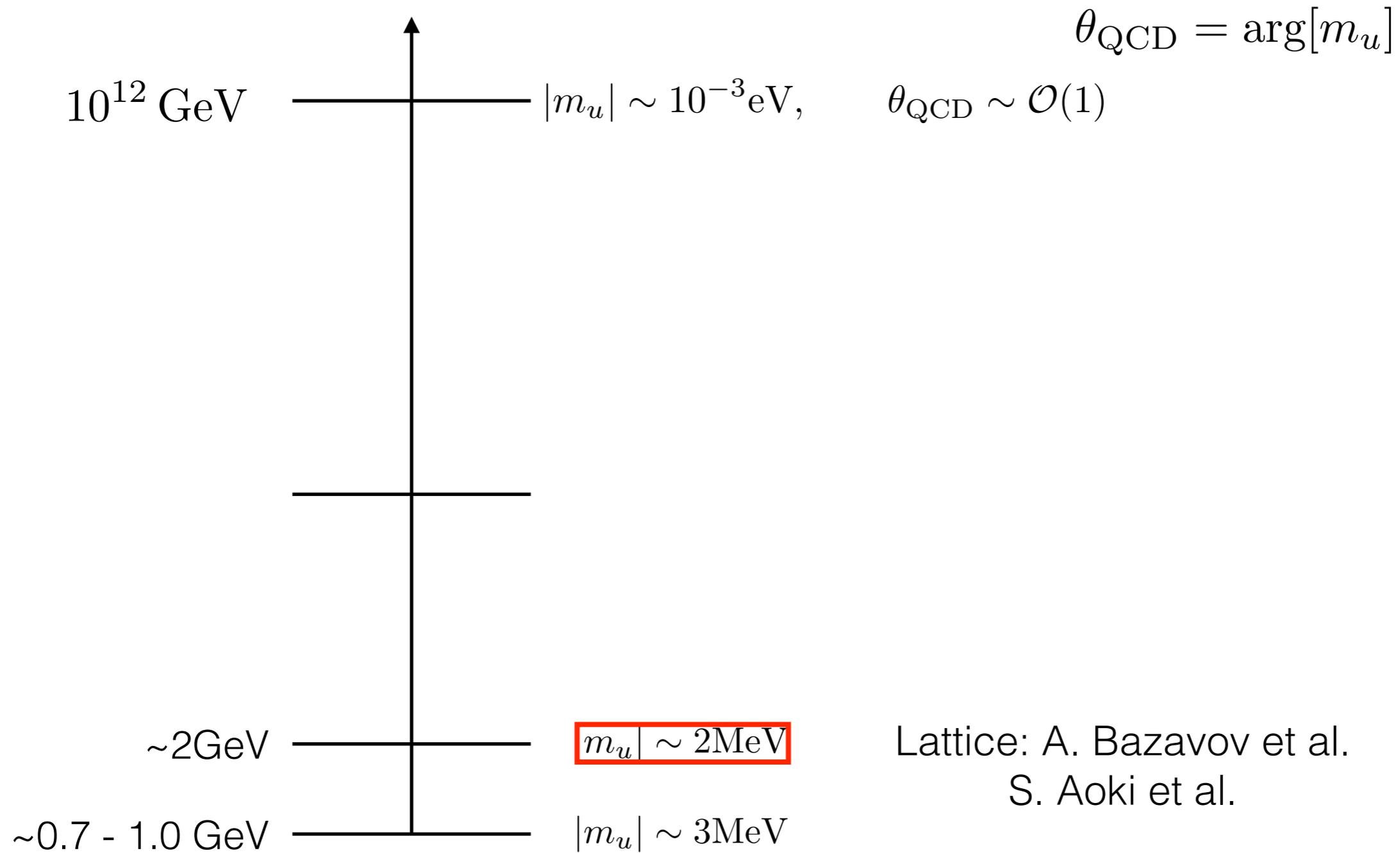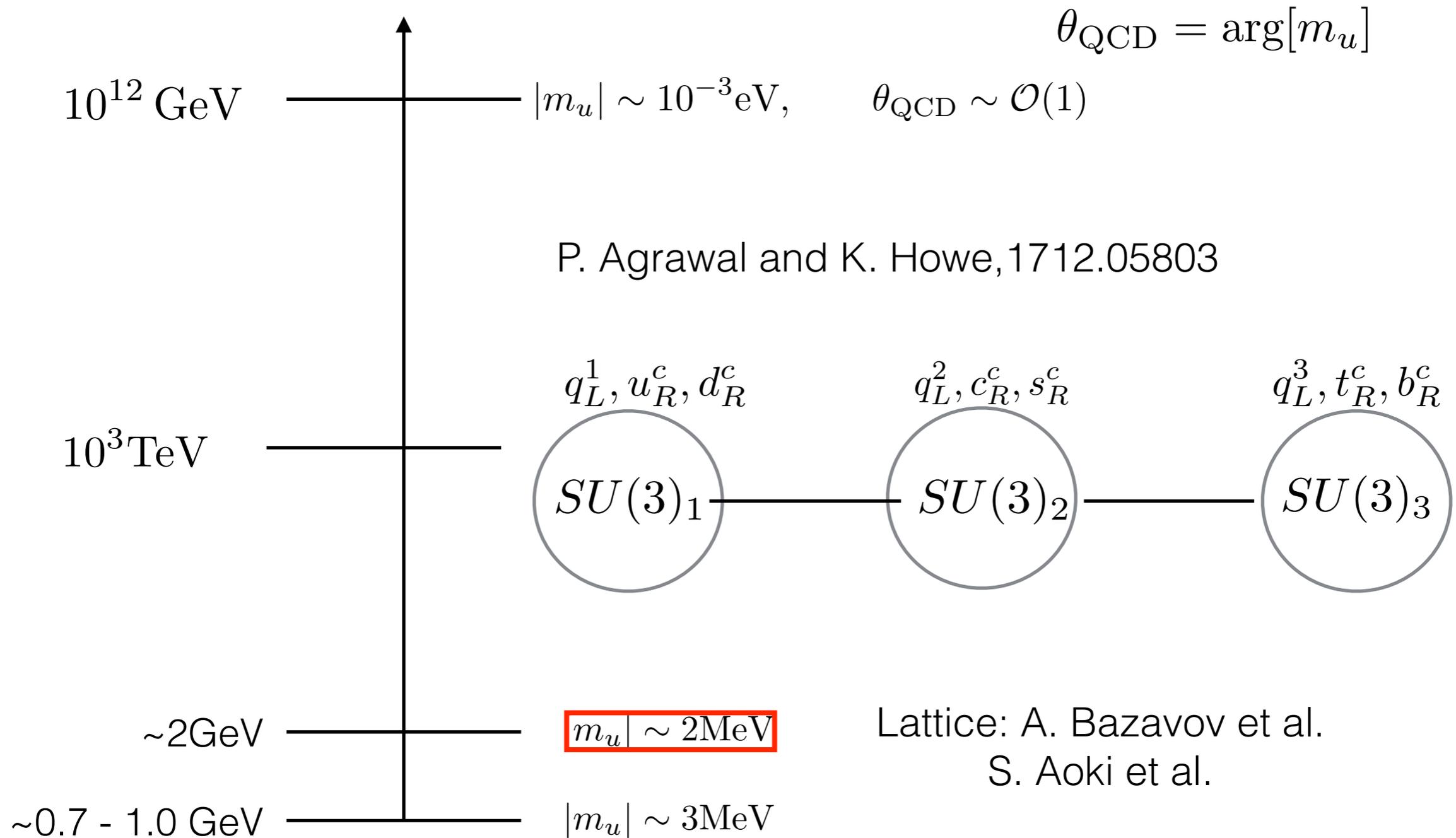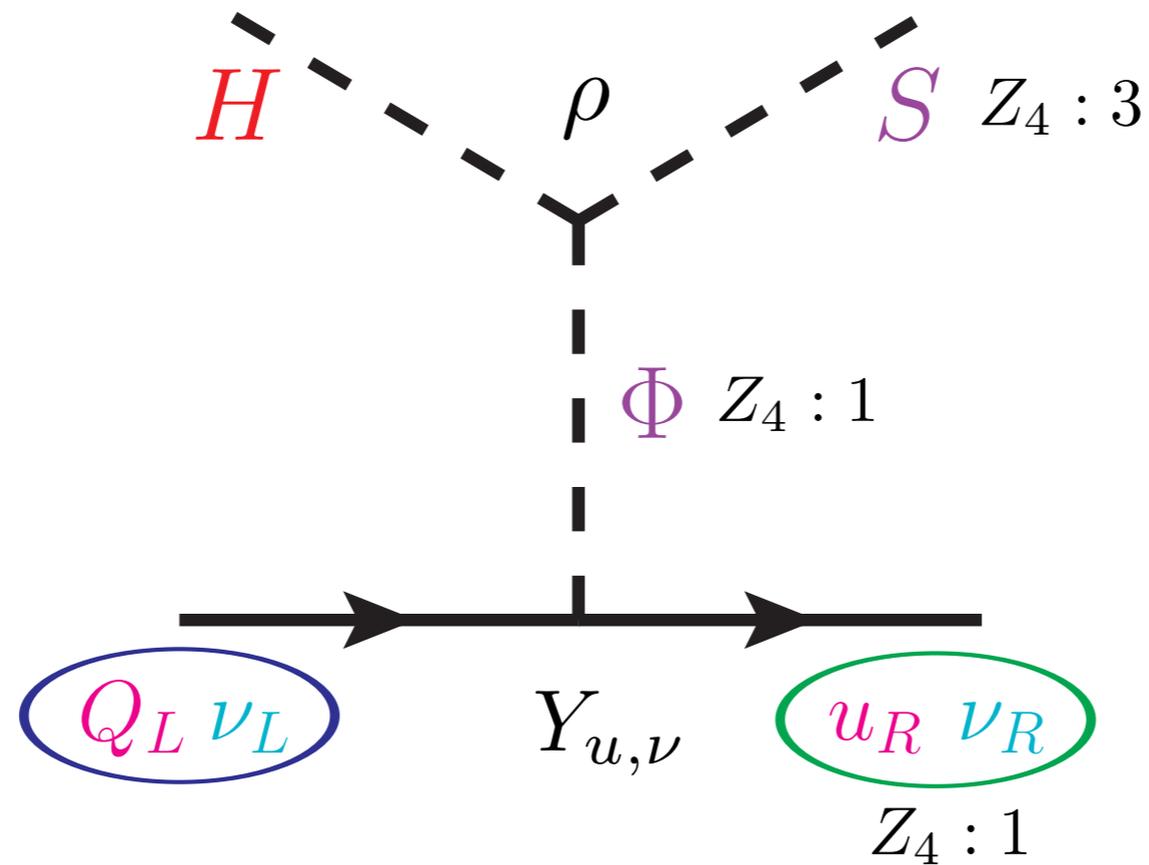
Dirac seesaw

P.-H. Gu and H.-J. He, hep- ph/0610275.

C. Bonilla, J. M. Lamprea, E. Peinado,

and J. W. F. Valle, 1710.06498

$$-Y_\nu \frac{\rho}{m_\Phi^2} S \bar{\ell}_L \tilde{H} \nu_R$$

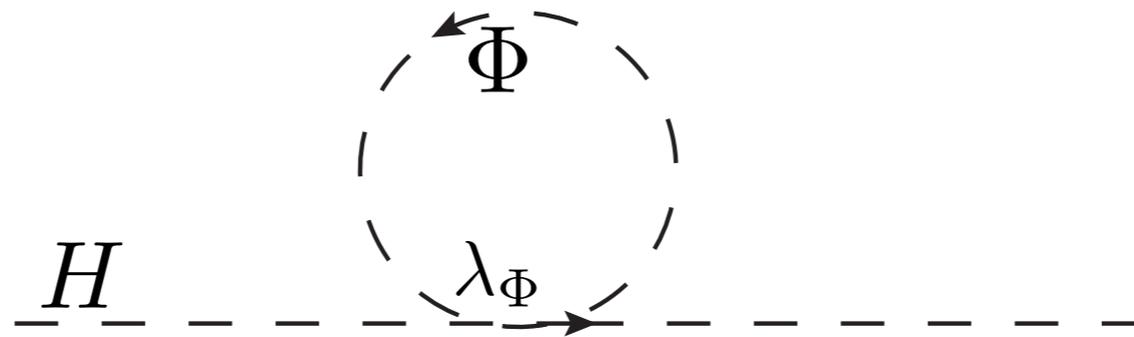$$-Y_u \frac{\rho}{m_\Phi^2} S \bar{q}_L \tilde{H} u_R$$

$$m_\nu \sim Y_\nu \frac{\rho \, v_S v}{2 m_\Phi^2}, \qquad m_u^H \sim Y_u \frac{\rho \, v_S v}{2 m_\Phi^2}.$$

$\lambda_S S^4$

No axion-like Goldstone!

Dirac seesaw

$$m_\Phi \simeq \boxed{6 \times 10^{12}\ \text{GeV}} \left(\frac{Y_\nu}{0.1}\right)\left(\frac{\rho}{0.1 m_\Phi}\right)\left(\frac{v_S}{v}\right),$$

leads to a physical contribution to the Higgs mass

$$\delta m_H^2 \sim \frac{\lambda_\Phi}{16\pi^2} m_\Phi^2$$

Need engineering $\qquad \lambda_\Phi \sim 10^{-19}$

SUSY extension

Superpotential

$$W = -Y_\nu L \Phi_u \nu_R^c - Y_u Q \Phi_u u_R^c$$

$$+\mu H_u H_d + m_\Phi \Phi_u \Phi_d + \lambda H_u \Phi_d S + \frac{\kappa}{3} S^3$$

Z_3

$$\Phi_u : 2, \quad \Phi_d : 1, \quad u_R^c : 1, \quad \nu_R^c : 1, \quad S : 2.$$

$$\mathcal{L}_{\text{eff}}^y = -Y_\nu \frac{\lambda}{m_\Phi} L H_u \nu_R^c S - Y_u \frac{\lambda}{m_\Phi} Q H_u u_R^c S + \cdots$$
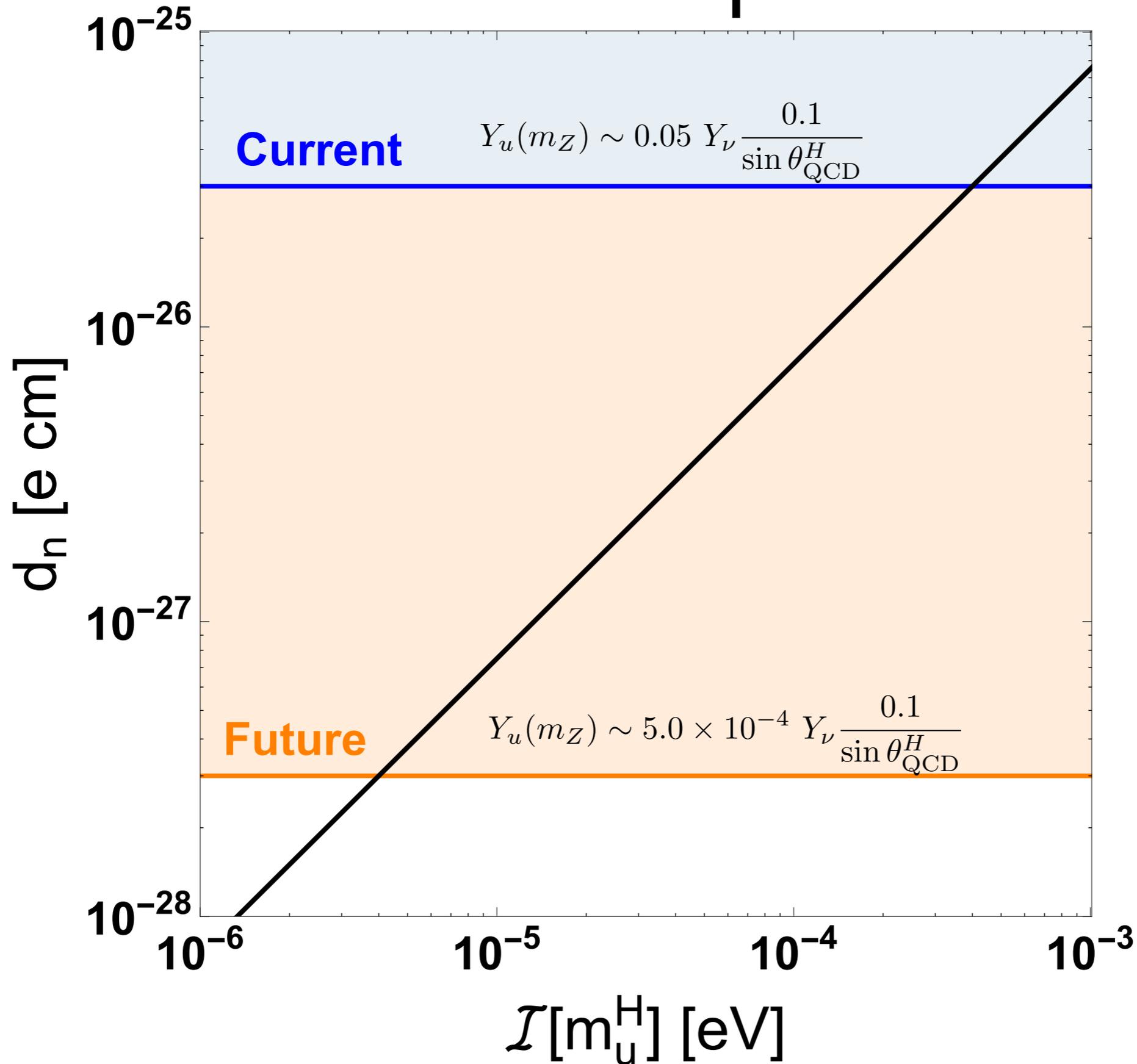
$$m_\nu \sim Y_\nu \frac{\lambda v_u v_S}{m_\Phi}, \qquad m_u^H \sim Y_u \frac{\lambda v_u v_S}{m_\Phi}.$$

nEDM experiments

Present Limit 3×10^{-26}e cm

Experiment	Sensitivity [e cm]
PSI	$< 1 \times 10^{-27}$
TRIUMF (TUCAN)	1×10^{-27}
SNS	$< 3 \times 10^{-28}$
PNPI-ILL-PTI	$10^{-27} - 10^{-28}$
LANL EDM	3×10^{-27}
Munich/ILL	$\mathcal{O}(10^{-28})$

nEDM Prospective

Conclusion

- A ν solution to Strong CP

- Dirac seesaw related two scale

$$m_\nu \text{ and } \text{Im}[m_u^H]$$

- A non-zero nEDM is predicted

- It is naturally within the reach of the next generation of experiments

Backup

$$\bar{g}_{\pi NN} = \theta_{\mathrm{QCD}} \frac{\mu_{eff}}{F_\pi} \frac{M_\Xi - M_N}{2|m_s| - |m_u| - |m_d|}, \qquad \mu_{eff} \equiv \frac{|m_u m_d m_s|}{|m_u m_d| + |m_u m_s| + |m_d m_s|},$$

$$\mathrm{NH} : m_3 \sim 0.05 \, \mathrm{eV}, \qquad m_2 \sim 0.0086 \, \mathrm{eV}$$

$$\mathrm{IH} : m_1 \sim 0.05 \, \mathrm{eV}, \qquad m_2 \sim 0.05 \, \mathrm{eV}$$

$$V_{\mathrm{SUSY}} = \mu^2 |H_u|^2 + |\mu H_d + \lambda \Phi_d S|^2 + |m_\Phi \Phi_u + \lambda H_u S|^2 + m_\Phi^2 |\Phi_d|^2 + |\kappa \, S^2 + \lambda H_u \Phi_d|^2, \tag{18}$$

$$V_{\mathrm{soft}} = m_{\Phi_u}^2 |\Phi_u|^2 + m_{\Phi_d}^2 |\Phi_d|^2 + m_S^2 S^* S + \cdots + (a_\lambda H_u \Phi_d S + b_\lambda \Phi_u^\dagger H_u S + a_\kappa S^3 + \cdots + h.c.),$$

$$\Lambda_\chi \sim 0.7 - 1.0 \, \mathrm{GeV}$$