Long-Lived Particles (LLP) and Displaced Vertices

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UNIVERSITY OF VIRGINIA

Windows on the Universe, Quy Nhon, August 5-11, 2018

Happy 25th Birthday to Rencontres du Vietnam!!!

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That being said...

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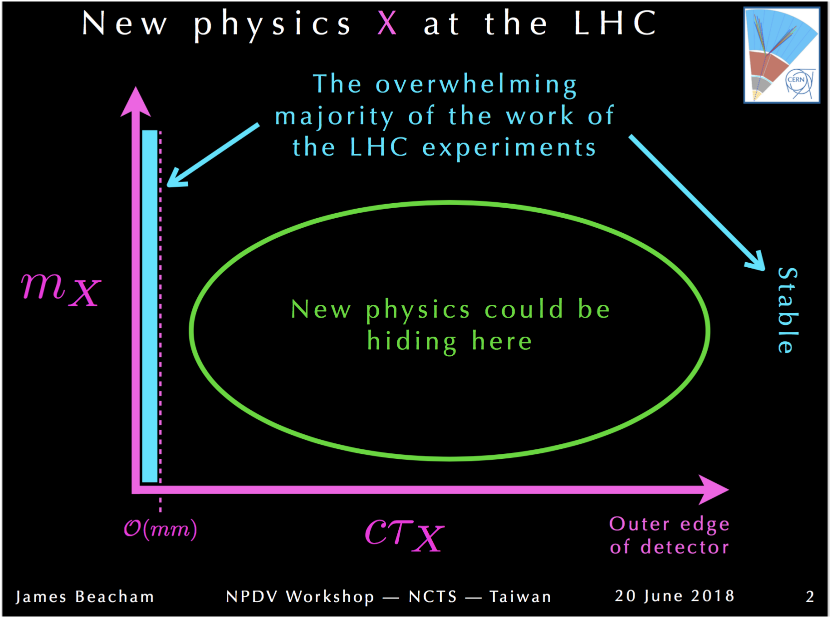
Are we looking at the right places?

What IF?



New physics X at the LHC

The overwhelming majority of the work of the LHC experiments

New physics could be hiding here

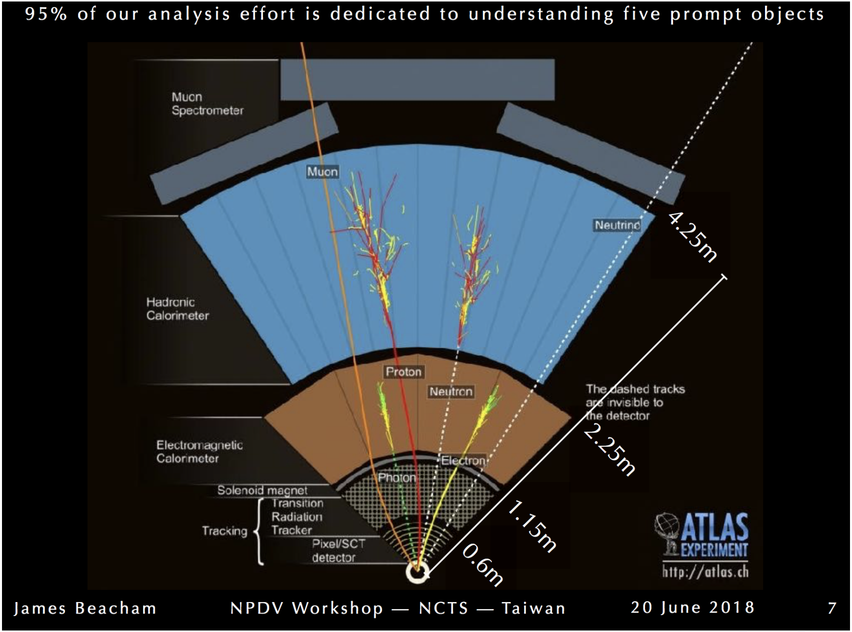
m_X

$c\tau_X$

$\mathcal{O}(mm)$

Outer edge of detector

Stable



95% of our analysis effort is dedicated to understanding five prompt objects

James Beacham NPDV Workshop — NCTS — Taiwan 20 June 2018 7

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Try to minimize moving the goalposts...

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Giant Isopod

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CLEARLY THE ONLY EVIDENCE OF BSM PHYSICS WE HAVE SO FAR!

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$\Rightarrow$ Existence of right-handed neutrinos.

Where are they?

Do they interact with W's and Z or not?

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Why should they be so???

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Right-handed neutrinos are non-sterile. They interact with W and Z. Their masses M_R are proportional to $\Lambda_{EW} \sim 246\,GeV$.

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- Experimental: They are "light" (LHC-accessible) and have typical electroweak production cross sections $\Rightarrow$ Direct test of seesaw.

- Theoretical: Deep connection between neutrino masses and the strong CP problem, among others.

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- How does one construct a model in which $M_R \propto \Lambda_{EW} \sim 246 GeV$ with ν_R carrying SM quantum numbers?
- Such a model has to first satisfy present experimental constraints!

Lee and Yang on Parity Violation:

"If such asymmetry is indeed found, the question could still be raised whether there could not exist corresponding elementary particles exhibiting opposite asymmetry such that in the broader sense there will still be over-all right-left symmetry.."

PR104, 254, October 1956.

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- $M_R \propto \Lambda_{EW}$? From the VEV of a triplet Higgs field $\tilde{\chi} = (\chi^0, \chi^+, \chi^{++})$ and lepton-number violating mass term

$$\boxed{L_M = g_M \, l_R^{M,T} \, \sigma_2 \, \tau_2 \, \tilde{\chi} \, l_R^M .}$$

The EW-ν_R model

- With $\langle \chi^0 \rangle = v_M < \Lambda_{EW}$, right-handed neutrino Majorana mass $\boxed{M_R = g_M v_M}$ $\Rightarrow$ $\boxed{M_Z/2 < M_R < O(\Lambda_{EW} \sim 246\,GeV)}$: Main point.

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- Wait! Isn't it too complicated? If M_R comes from symmetry breaking, it's unavoidable to have a Higgs structure larger than that of the SM. E.g. 126 of SO(10) or a triplet Δ_R of L-R model.

The EW-ν_R model

- m_D?

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- m_D? From the VEV of a complex singlet Higgs field ϕ_S. Lepton-number conserving term $\boxed{\mathcal{L}_S = -g_{Sl}\,\bar{l}_L\,\phi_S\,l^M_R + \mathrm{H.c.}}$ $\boxed{m_D = g_{Sl}\,v_S}$ where $\boxed{\langle\phi_S\rangle = v_S}$. Crucial in the discussion of the phenomenology of the model and the strong CP problem

The EW-ν_R model

- $l_R^M = \begin{pmatrix} \nu_R^M \\ e_R^M \end{pmatrix}$: Anomaly cancellation $\rightarrow$ Mirror quarks: $q_R^M = \begin{pmatrix} u_R^M \\ d_R^M \end{pmatrix}$

Summary of the EW-ν_R model

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- Scalars:
  * Doublet Higgs fields (similar to 2HDM): $\Phi_1^{SM}(Y/2 = -1/2)$, $\Phi_2^{SM}(Y/2 = +1/2)$ coupled to SM fermions, and $\Phi_1^M(Y/2 = -1/2)$, $\Phi_1^M(Y/2 = +1/2)$ coupled to mirror fermions with $\langle \Phi_1^{SM} \rangle = (v_1/\sqrt{2}, 0)$, $\langle \Phi_2^{SM} \rangle = (0, v_2/\sqrt{2})$ and $\langle \Phi_1^M \rangle = (v_1^M/\sqrt{2}, 0)$, $\langle \Phi_2^M \rangle = (0, v_2^M/\sqrt{2})$.

Summary of the EW-ν_R model

*Triplet Higgs fields:

$$\chi = \begin{pmatrix} \chi^0 & \xi^+ & \chi^{++} \\ \chi^- & \xi^0 & \chi^+ \\ \chi^{--} & \xi^- & \chi^{0*} \end{pmatrix}$$

$\xi\ (Y/2 = 0) = (\xi^+, \xi^0, \xi^-)$ with $\langle \chi^0 \rangle = \langle \xi^0 \rangle = v_M$ in order to preserve Custodial Symmetry (that guarantees $M_W^2 = M_Z^2 \cos^2\theta_W$ at tree level.
Here $(\sum_{i=1,2} v_i^2 + v_i^{M,2}) + 8v_M^2 = (246\,GeV)^2$.

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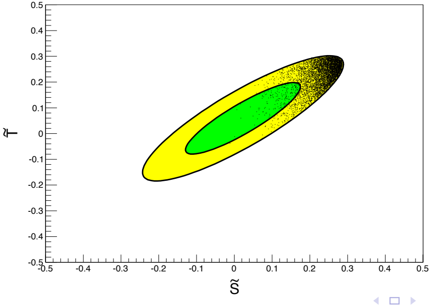
*So many Higgs fields? Nothing to be afraid of. Good hunting ground!

Summary of the EW-ν_R model: Precision constraints

Fig. 1 and 2 are the 1σ and 2σ constraints. $\tilde{T}$ and $\tilde{S}$ are the total contributions (mirror fermions plus scalars) after subtracting out the SM contributions.



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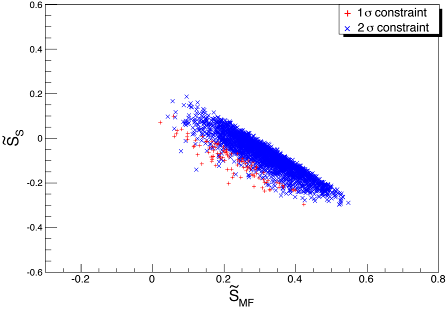
$\tilde{S}_S$ and $\tilde{S}_{MF}$ are the contributions to S from the scalars (mainly the triplets) and the mirror fermions.



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- Notice that, for a large range of parameters, the contribution to $\tilde{S}_S$ from Triplet scalars is generally negative and large (see the previous figure)!
- If only triplet scalar is present $\Rightarrow$ very small region of parameter space for $\tilde{S}_S$ is allowed $\Rightarrow$ fine-tuning problem! The much larger parameter space which allows mass splitting inside the triplet has large and negative values for $\tilde{S}_S$ which need to be cancelled by similar positive amount coming from another sector such as the mirror fermion sector! One cannot play around with triplet Higgs without experimental consequences!

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Some examples on the next slide

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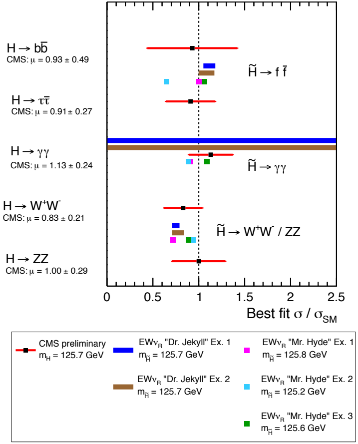

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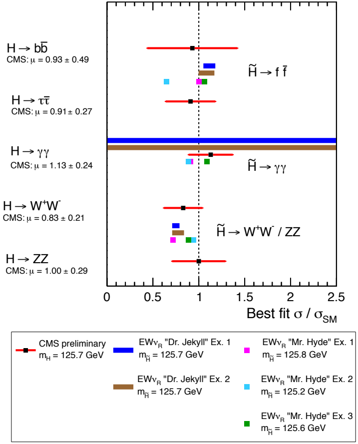

We need to measure the partial widths to know the true nature of the 125-GeV!

Higgs factory? Unless...

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- Like-sign dileptons $e_{Lk} + e_{Ll}$ plus 4 jets (from 2 W) plus missing energies (from ϕ_S) ⇒ Lepton-number violating signals!

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- Calculations of $\mu \to e\gamma$ and μ to e conversion in the model give a general constraint on those Yukawa couplings $\boxed{g_{Sl} < 10^{-4} \Rightarrow \text{Could have decay lengths} > 1\text{mm}}$! How does one handle that?

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- The appearance of $\boxed{\text{like-sign dileptons}}$ $(e^- e^-, \mu^- \mu^-, \tau^- \tau^-, e^- \mu^-, ...)$ could be at $\boxed{\text{displaced vertices}}$.

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- Constraint on $\bar{\theta}$ $\Rightarrow$ Constraint on $\boxed{g_{Sq} < g_{Sl}}$ $\Rightarrow$ Displaced vertices in mirror quark decays.

g_{S_q} constraint from the strong CP problem

- The vacuum of QCD is complicated. 't Hooft: The proper gauge-invariant vacuum is characterized by an "angle" $|\theta\rangle = \sum_n \exp(-\imath n\,\theta)|n\rangle$

  $\Rightarrow \boxed{S_{eff} = S_{gauge} + \theta_{QCD}\,(g_3^2/32\pi^2)\int d^x\, G_a^{\mu\nu}\,\tilde{G^a_{\mu\nu}}}$

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- $\theta_{QCD} < 10^{-10}$. Why is it so small? That is the strong CP problem.

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- Diagonalization of quark mass matrices ⇒ $\theta_{QCD} \to \bar{\theta} = \theta_{QCD} + ArgDetM$
- Solution to the strong CP problem: How to make 1) $\theta_{QCD} = 0$, 2) $ArgDetM = 0$ or $< 10^{-10}$?

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- Peccei and Quinn: Extra global symmetry $\boxed{U(1)_{PQ}}$ (chiral) and $\bar{\theta}$ is replaced by an axion field $a(x)$ where the minimum of an (quite complicated) effective potential is where the effective θ is zero.

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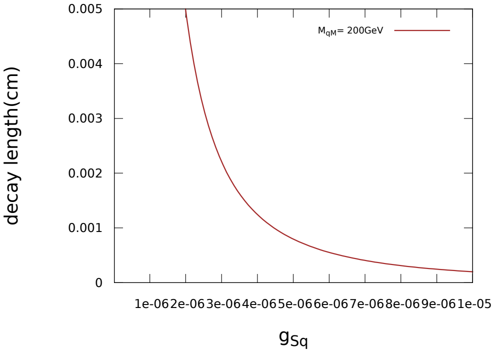
Search for mirror quarks

$\boxed{q_R^M \rightarrow q_L + \phi_S}$. Example::

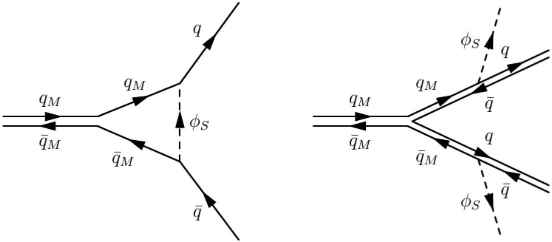
Typical decay length $\gg$ Hadronization length $\sim O(1 fermi)$

$\bar{q}^M q^M$ mesons get formed first before they decay!



Search for mirror quarks

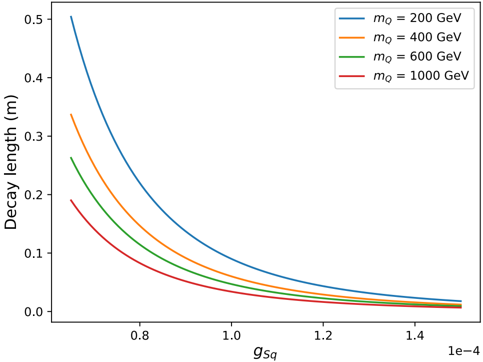
Mirror-meson decays



Search for mirror quarks

Mirror-meson decay lengths:

Displaced Vertices $> O(cm)$ for $g_{Sq} < 10^{-4}$.



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- The EW-scale ν_R model provides a test of the seesaw mechanism at collider energies since ν_R's are now fertile and "light"! Rich studies involving the search for the mirror sector at the LHC with in particular characteristic signals such as $\boxed{\text{DISPLACED VERTICES}}$. Mirror fermions are $\boxed{\text{Long-Lived-Particles}}$!

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- Nielsen-Ninomiya theorem: The EW-scale ν_R model evades the N-N theorem and one can now study EW phase transition on the lattice.
- If space is indeed discrete at the Planck scale then the Nielsen-Ninomiya no-go theorem requires the existence of mirror fermions. Deep implications for Quantum Gravity?

And...

Cam on and Long live Rencontres du Vietnam!

Some papers

- EW-scale nu_R model; PQH, Phys. Lett. B **649**, 275 (2007).
- EW precision: V. Hoang, P. Q. Hung and A. S. Kamat, Nucl. Phys. B **877**, 190 (2013) doi:10.1016/j.nuclphysb.2013.10.002 [arXiv:1303.0428 [hep-ph]].
- 125-GeV scalar: V. Hoang, P. Q. Hung and A. S. Kamat, Nucl. Phys. B **896**, 611 (2015) doi:10.1016/j.nuclphysb.2015.05.007 [arXiv:1412.0343 [hep-ph]].
- Rare decays: P. Q. Hung, T. Le, V. Q. Tran and T. C. Yuan, JHEP **1512**, 169 (2015) doi:10.1007/JHEP12(2015)169 [arXiv:1508.07016 [hep-ph]].

Some papers

- Searches: S. Chakdar, K. Ghosh, V. Hoang, P. Q. Hung and S. Nandi, Phys. Rev. D **93**, no. 3, 035007 (2016) doi:10.1103/PhysRevD.93.035007 [arXiv:1508.07318 [hep-ph]], S. Chakdar, K. Ghosh, V. Hoang, P. Q. Hung and S. Nandi, Phys. Rev. D **95**, no. 1, 015014 (2017) doi:10.1103/PhysRevD.95.015014 [arXiv:1606.08502 [hep-ph]].
- strong CP:arXiv:1704.06390 [hep-ph];mirror fermion searches:Phys. Lett. B **649**, 275 (2007); Phys. Rev. D **95**, no. 1, 015014 (2017);Phys. Rev. D **93**, no. 3, 035007 (2016),..
- More are in preparation.

Backup slides

- Peccei and Quinn solution:
  Extra global symmetry $U(1)_{PQ}$ (chiral)
- P-Q Toy model: Single flavor ψ interacting with a scalar ϕ ; Chiral symmetry $U(1)_A$ (or $U(1)_{PQ}$). Lagrangian invariant under a chiral rotation
  $\psi \rightarrow \exp(\imath\sigma\gamma_5)\psi$; $\phi \rightarrow \exp(-\imath 2\sigma)\phi$
- Jackiw-Rebbi: $\theta_{QCD} \Rightarrow \theta_{QCD} - 2\sigma \Rightarrow$ All vacuua are equivalent $\Rightarrow$ one can rotate θ_{QCD} to zero! No CP violation!
- Peccei and Quinn have proved that 1) $\langle\phi\rangle = 0 \Rightarrow$ No CP violation; 2) even if $\langle\phi\rangle \neq 0$ No CP violation if $\bar{\theta}$ is replaced by an axion field $a(x)$ where the minimum of an (quite complicated) effective potential is where the effective θ is zero.
- Visible axion ruled out by beam dump experiment. Invisible axion not found after more than 30 years or so.

The strong CP problem: Brief review

- There are several axionless models for the strong CP problem: Nelson, Barr,...

Neutrinos and the strong CP problem

Ingredients of the EW-ν_R model which help solve the strong CP problem without an axion.

- Mirror fermions.
- Mixing of mirror with SM fermions ⇒ Dirac mass of neutrinos through $g_{Sl}\bar{l}_L \phi_S l_R^M$.
- A global symmetry $U(1)_{SM} \times U(1)_{MF}$ was imposed to prevent terms such as $\bar{l}_L \tilde{\chi} l_R^M$ (Dirac mass too big); $l_L^T \ \sigma_2 \ \tau_2 \ \tilde{\chi} \ l_L$ (gives rise to unwanted $\nu_L^T \nu_L$),..which spoil the seesaw mechanism.

What do the above ingredients have to do with the strong CP problem?

Neutrinos and the strong CP problem

- Most of salient points concerning the solution to the strong CP problem can be obtained with a toy model with one family.
- Relevant Yukawa interactions
  $\mathcal{L}_{mass} =$
  $g_u \bar{q}_L \Phi_1^{SM} u_R + g_d \bar{q}_L \Phi_2^{SM} d_R + g_u^M \bar{q}_R^M \Phi_1^M u_L^M + g_d^M \bar{q}_R^M \Phi_2^M d_L^M + H.c.\,,$
  $\mathcal{L}_{mixing} = g_{Sq} \bar{q}_L \phi_S q_R^M + g_{Su} \bar{u}_L^M \phi_S u_R + g_{Sd} \bar{d}_L^M \phi_S d_R + H.c.\,.$
- Step 1 of the solution to strong CP (Peccei-Quinn): Use a chiral symmetry to rotate away θ_{QCD}.
  $\mathcal{L}_{mixing}$ and $\mathcal{L}_{mass}$ are invariant under: $q \rightarrow \exp(\imath \alpha_{SM} \gamma_5) q$; $q^M \rightarrow \exp(\imath \alpha_{MF} \gamma_5) q^M$; $\phi_S \rightarrow \exp(-\imath(\alpha_{SM} + \alpha_{MF}))\phi_S$ under the chiral symmetries $U(1)_{A,SM} \times U(1)_{A,MF}$ contained in $U(1)_{SM} \times U(1)_{MF}$. Jackiw-Rebbi: $\theta_{QCD} \rightarrow \theta_{QCD} - (\alpha_{SM} + \alpha_{MF})$
- All vacuua are equivalent and one can choose the CP-conserving vacuum $\theta_{QCD} - (\alpha_{SM} + \alpha_{MF}) = 0$.

Neutrinos and the strong CP problem

- Notice that g_u, g_d, g_{u^M}, g_{d^M}, g_{Sq}, g_{Su} and g_{Sd} can, in general be complex. If we absorb the phases into u_R, u_L^M, d_R and d_L^M to make the *diagonal* elements of the (2×2) up and down mass matrices *real* then the *off-diagonal* elements stay *complex*.

$$\mathcal{M}_u = \begin{pmatrix} m_u & |g_{Sq}| v_S \exp(\imath\theta_q) \\ |g_{Su}| v_S \exp(\imath\theta_u) & M_u \end{pmatrix} \tag{1}$$

$$\mathcal{M}_d = \begin{pmatrix} m_d & |g_{Sq}| v_S \exp(\imath\theta_q) \\ |g_{Sd}| v_S \exp(\imath\theta_d) & M_d \end{pmatrix} \tag{2}$$

Neutrinos and the strong CP problem

- Step 2 of the solution to the strong CP problem: Calculation of $ArgDet\mathcal{M}_u\mathcal{M}_d$. Call that θ_{weak}.
- $\boxed{\theta_{Weak} \approx -(r_u \sin(\theta_q + \theta_u) + r_d \sin(\theta_q + \theta_d))}$

  $r_u = \frac{|g_{Sq}||g_{Su}|v_S^2}{m_u M_u} = (\frac{|g_{Sq}||g_{Su}|}{g_{Sl}^2})(\frac{m_D^2}{m_u M_u})$

  $r_d = \frac{|g_{Sq}||g_{Sd}|v_S^2}{m_d M_d} = (\frac{|g_{Sq}||g_{Sd}|}{g_{Sl}^2})(\frac{m_D^2}{m_d M_d})$

  $m_D = g_{Sl} v_S$: Dirac mass in seesaw.

  $m_\nu = m_D^2/M_R$
- Important remark: Even with maximal CP phases $\theta_q + \theta_{u,d} = \pi/2$, $\theta_{weak} \to 0$ if $r_{u,d} \to 0$.
- Assuming $g_{Sq}, g_{Su}, g_{Sd} \neq 0$, $\theta_{weak} \to 0$ if $v_S \to 0$ *or* $m_\nu \to 0$.
- Smallness of neutrino mass ⇒ smallness of $\bar{\theta}$! No need to make $\bar{\theta}$ zero.

Neutrinos and the strong CP problem

- Putting in numbers

$$\boxed{\theta_{Weak} < -10^{-8}\{(\frac{|g_{Sq}||g_{Su}|}{g_{Sl}^2})\sin(\theta_q + \theta_u) + (\frac{|g_{Sq}||g_{Sd}|}{g_{Sl}^2})\sin(\theta_q + \theta_d)\}}$$

- Without fine tuning, this implies $\boxed{|g_{Sq}| < |g_{Sl}| < 10^{-4}}$ ⇒ Displaced vertices for the mirror quarks too!
- How small would the neutron electric dipole moment be? It appears to be intrinsically tied to the absolute mass of the neutrinos!