Strong CP Problem and energy independent test of Left Right Symmetric Model.

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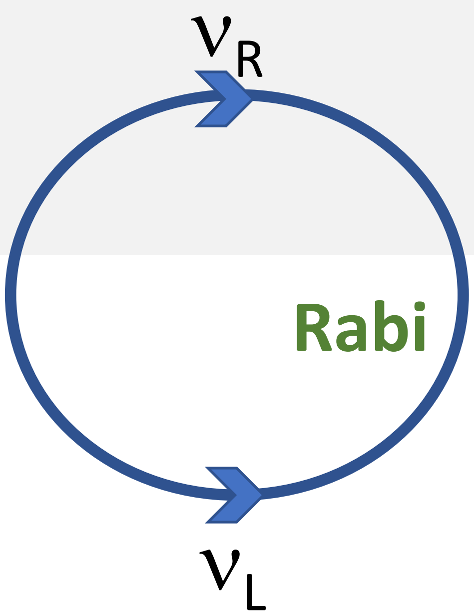


Rabi Fest, University of Maryland 2022

CP | P ✓

CP is violated by the CKM phase

However the strong CP phase $\bar{\theta}$ < 10^{-10}
($\bar{\theta}$ requires both P and CP violation)

Q: Is P violated by SM Yukawa couplings h_q with Higgs boson?

Minimal Left-Right symmetric model with Parity (LR model):
$\bar{\theta} \approx 0 \Rightarrow h_q$ *remain* Hermitian **(conserve P)** just below $LR \rightarrow SM$ scale.

P | CP ✓

P is violated by neutrino masses (seesaw mech)
(Dirac mass less than few MeV for m_{ν_3} not technically natural in LR model)

Q: Is CP violated by leptonic Yukawa couplings?

LR Model: If CP is also violated, there is no protection for the strong CP phase and it is generated in one-loop (unsuppressed by large mass scales).

Prediction: $\delta_{CP} = 0 \; or \; \pi$ **(Dirac CP phase of PMNS matrix)**
in most of the parameter space, regardless of the high energy scale where LR symmetry breaks.

SURPRISING/SHOCKING result of LR model that is testable

LR Model: $SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times P$

Goran, Rabi ('75); Rabi, Pati ('75); Pati, Salam ('74)

$\Delta_L(3,1,2), \Delta_R(1,3,2), \phi(2,2,0)$ (ϕ has two SM Higgs doublets H_1 , H_2)

$P: \phi \to \phi^\dagger, L \leftrightarrow R$

$Q_{iL}(2,1,\frac{1}{3})$, L_{iL} $(2,1,-1)$, $Q_{iR}(1,2,\frac{1}{3})$, $L_{iR}(1,2,-1)$

Higgs pot. term: $\mu^2 H_1 H_2 + hc$ **μ^2 is real (CP conserving) due to P.**

No hierarchy problem associated fine tuning in CP violating terms.
Therefore, Strong CP phase calculation is clean.

$\bar{\theta} = \theta_{QCD} + Arg\ Det\ M_q$ θ_{QCD} absent due to P

$M_q = vh_q$ Yukawas h_q - Hermitian due to P.

Imaginary part of VEV v_2 of H_2 generates $\bar{\theta}$.

$< \phi > = \begin{pmatrix} v_1 & o \\ 0 & v_2 \end{pmatrix}$

Only CP violating term in Higgs pot.: $\alpha_2 Tr\ (H_1 H_2 \Delta_R^\dagger \Delta_R) + R \to L, \phi \to \phi^\dagger$

$$\bar{\boldsymbol{\theta}} \sim h_t\ \{\text{Im}\ v_2\}\ /m_b \sim h_t\ \{(\alpha_{2i} v_{wk}\ v_R^2)/(\alpha_3 v_R^2)\}/m_b \sim (\boldsymbol{m_t}/\boldsymbol{m_b})(\boldsymbol{\alpha_{2i}}/\boldsymbol{\alpha_3})$$

$h_t v_2$ -- contribution to b mass from top Yukawa coupling.

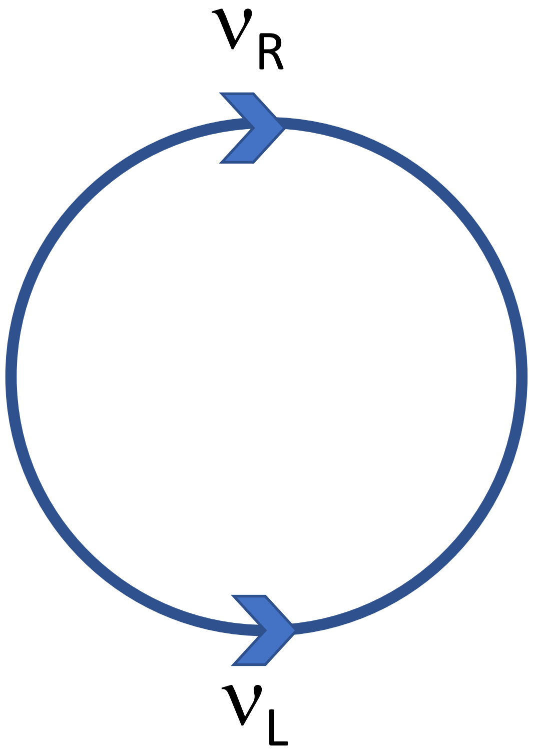
α_{2i} -- imaginary part of α_2, $v_1 = v_{wk}$ -- VEV of H_1 , v_R -- VEV of Δ_R

$(\alpha_3 v_R^2/2)$ – mass^2 of second Higgs doublet H_2 ($\alpha_3 \leq 1$ is a quartic coupling)

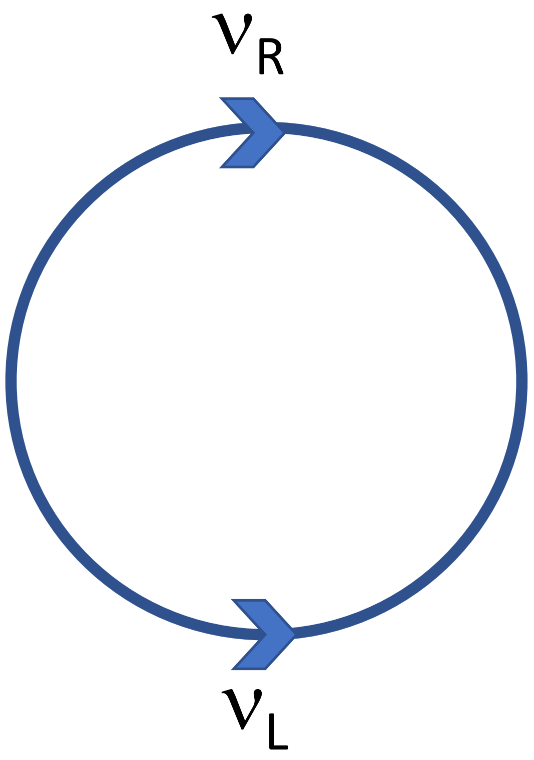
$$\bar{\boldsymbol{\theta}} < \mathbf{10^{-10}} \Rightarrow |\boldsymbol{\alpha_{2i}}| \leq \mathbf{2 \times 10^{-12}}$$

RK 2014 (PRD) arXiv 1408.6382

For Rabi: Trillion TeV *NEUTRINO* Collider

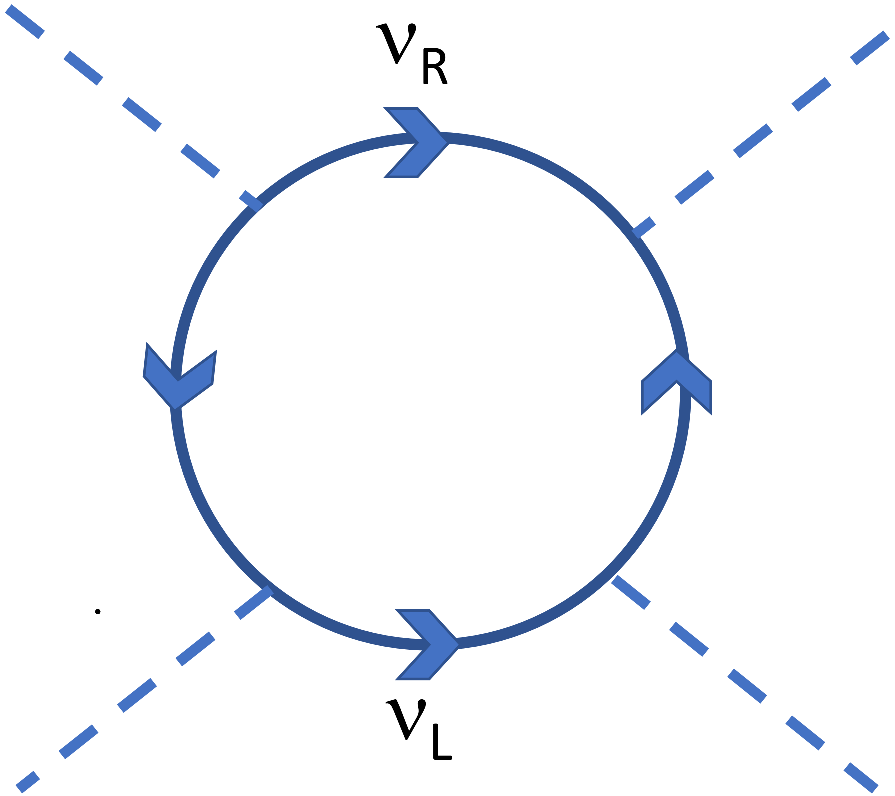


For Rabi: Trillion TeV *NEUTRINO* Collider



However this technology got obsolete 13.8 billion years ago.

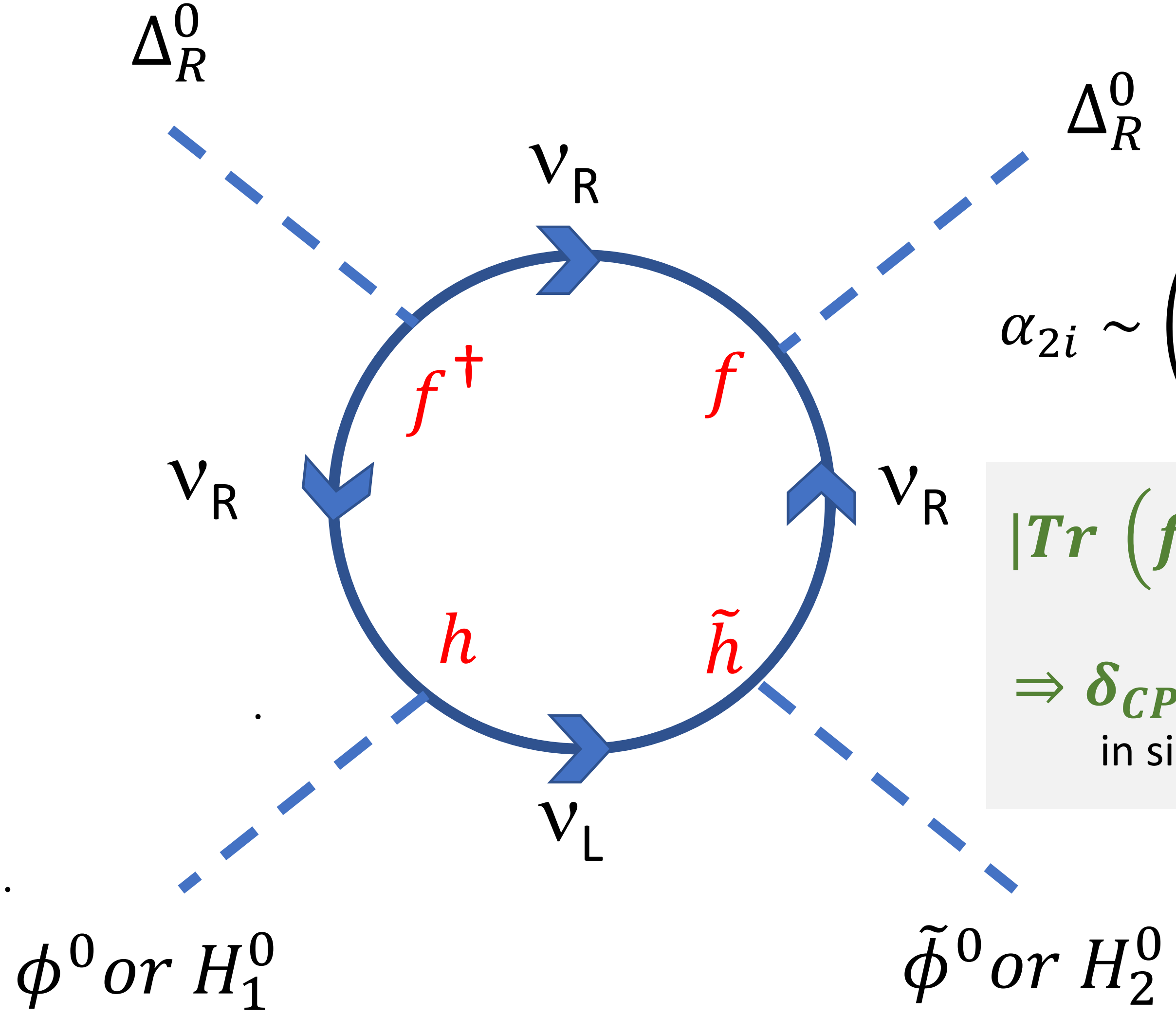
For Rabi: Trillion TeV *NEUTRINO* Collider



AVAILABLE TODAY

With virtual neutrinos

In Stock, Ships Free



$$\alpha_{2i} \sim \left(\frac{1}{16\pi^2}\right) Im\ Tr\left(f^\dagger f \tilde{h} h\right) Ln\left(\frac{M_R}{M_{Pl}}\right)$$

$$|Tr\left(f^\dagger f[\tilde{h}h - h\tilde{h}]\right)| \ \leq 3 \times 10^{-11}$$

$\Rightarrow \delta_{CP} = 0\ or\ \pi$ (Dirac CP phase of PMNS) in significant parameter space of LR model.

$h, \tilde{h}$ Hermitian due to P (Dirac)

$P:\ f_L = f_R = f$ (Majorana)

RK 2014 (PRD) arXiv 1408.6382

Physically Interesting regions

$$Tr\left(f^{\dagger}f[\tilde{h}h - h\tilde{h}]\right) \sim \left|(\sin\delta_{CP})h_{33}\tilde{h}_{32}f_{23}f_{33}\right| \leq 3\times 10^{-11}$$

Charged lepton masses are similar to quark down sector masses --

Motivates $h_{33}\tilde{h}_{32} \sim h_t h_b V_{bc} \sim 10^{-3}$

("high" value probes highest seesaw scale: up to $10^{15}GeV!$)

If B-L gauge symmetry breaks at or around Seesaw scale – $f_{23}f_{33} \sim 10^{-2}\ to\ 1$

Therefore $|\sin\delta_{CP}|$ must be negligibly small (its smallness is technically natural)

$\boldsymbol{Expect\ \delta_{CP} = 0\ or\ \pi\ \ (testable\ by\ neutrino\ experiments)}$

10 TeV scale LR probed by "lower value" $h_{33}\tilde{h}_{32} \sim 10^{-7\ to\ -8}$ (also **expect** if $f_{33} \sim 1$)

$\theta_{QCD} = 0$ not a necessary condition to obtain our result

$$\bar{\theta}_{Tree\ Level} + \bar{\theta}_{One\ Loop}$$

$$\left(\theta_{QCD} + Arg\ Det\ M_q\right)_{Tree\ Level} + \left(Arg\ Det\ M_q\right)_{One\ Loop}$$

Too large unless leptonic CP phases vanish.

(in significant part of parameter space)

Note that this term's naturalness issue is indifferent to value of θ_{QCD}

Strong CP solution using LR model

1978 *(Rabi, Goran)* Suggest LR model maybe used to solve strong CP problem. However adding symmetries to LR model to prevent α_{2i} and more Higgses to break them does not work. Either δ_{CKM} and $\bar{\theta}$ both get generated at tree level or neither get generated.

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1996 – SUSY solves strong CP problem in LR model *(RK '96; Rabi, Rasin '96)*. $\alpha_2$term absent in SUSY. However Q_{em}spontaneously breaks in miminal SUSYLR model unless R-Parity is broken or additional Higgs are added *(RK, Rabi '91)*. Strong CP solution not as clean as it looks.

2010 – NON-SUSY LR SOLUTION Impose $P \times CP$ $(\equiv P \times T)$ Add a heavy vector like quark $SU(2)_L$doublet Q_{4L}, Q'_R (and $SU(2)_R$doublet counterpart Q_{4R}, Q'_L).
$\Sigma M_i \bar{Q}_{iL} Q'_R + M_i^{\star} \bar{Q}'_L Q_{iR}$ -- P symmetric mass-terms with usual quarks. CP softly violated by these terms or spontaneously broken by also adding a CP odd P even real scalar singlet.
Unsuppressed $\delta_{CKM} \sim 1$ generated below heavy quark mass scale, no tree-level α_{2i} and $\bar{\theta}$.

-- No leptonic CP phases generated either! (in minimal versions)
Was first indicator that $\delta_{CP} = 0 \; or \; \pi$ is likely in LR model. *RK 2010 (PRD) arXiv 1009.5961*

Choice of intrinsic parity if we want to add a Vector like heavy lepton family

RK 2012 (EPJC) arXiv 1209.3031

-- **If under P:** $\boldsymbol{L_{L,R}^{heavy} \to iL_{R,L}^{heavy}}$ $\quad(\boldsymbol{L_{L,R}^{usual} \to L_{R,L}^{usual}})$

then $P^2 \equiv Z_2$ is an automatic symmetry (P implies P^2) and remains unbroken.

Lowest mass heavy lepton stable – **dark matter stabilized by Parity!**
Doesn't couple with usual leptons, **doesn't generate leptonic CP violation.**

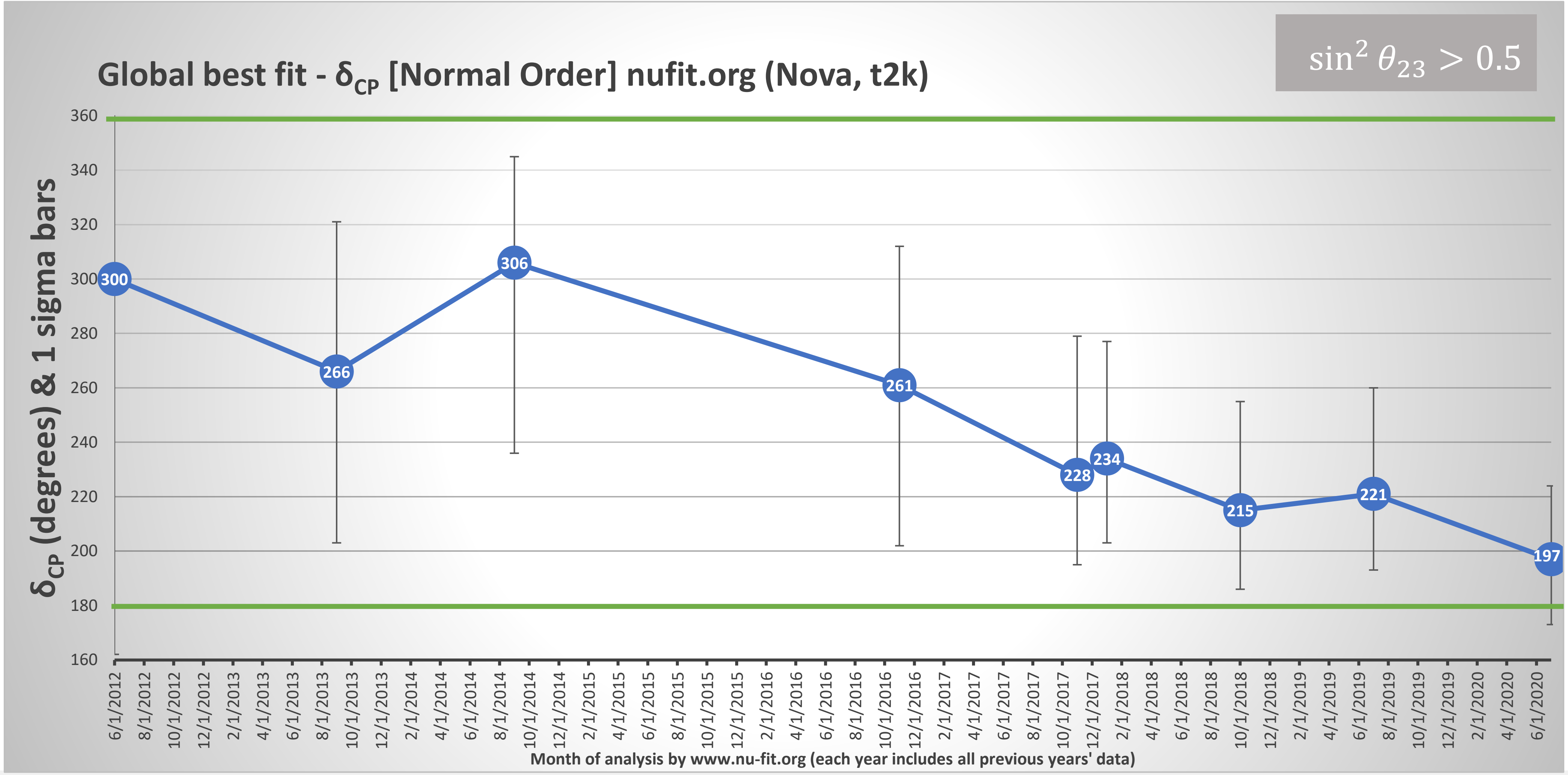
Above choice not there for quarks: $P^2 = 1$ $(U(1)_B$rotates imaginary intrinsic parity phase away).

-- **If under P:** $\boldsymbol{L_{L,R}^{heavy} \to L_{R,L}^{heavy}}$

Leptonic CP violation generated.

But if L^{heavy} heavier than M_R, then leptonic δ_{CP} will generate α_{2i} *and* $\bar{\theta}$ in one loop as we already saw, which is not healthy.

If L^{heavy} lighter than M_R, then no effective "*minimal*" LR model. CP violation generated below P breaking scale. **Maybe these heavy leptons can be discovered at the TeV scale!**



LR model expectation: ——— **EAGERLY WAITING FOR MORE DATA & DUNE, HYPER-K**

Results of this work are for: $SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times \boldsymbol{P}$ *and* $SU(4)_C \times SU(2)_L \times SU(2)_R \times \boldsymbol{P}$

Route to $\boldsymbol{SO(10)}$ **--** $SU(2)_L \times SU(2)_R \times U(1)_{B-l} \times \boldsymbol{C}$ *and* $SU(4)_C \times SU(2)_L \times SU(2)_R \times \boldsymbol{C}$

Reminder to myself:

This is a talk on the Strong CP problem.

Mention axions at least once.

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Mention axions at least once.

They don't pass muster if $sin(\delta_{CP}) = 0$

Have always admired the tremendous pace and depth of your work in so many areas Prof Mohapatra! And sense of humor, which is naturally real to you. There is no retiring from Physics.

Im(retirement)/Re(retirement) $\rightarrow \infty$