Left-Right Symmetry with Dirac neutrinos

Quiet phenomenology, right-handed flavour, and strong CP

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PMNS is measured. Is there a right-handed counterpart?

$$V_L^{(\ell)} \simeq U_{\mathrm{PMNS}}$$

Measured by oscillations: $\{\theta_{12}, \theta_{13}, \theta_{23}, \Delta m_{ij}^2, \delta_{\mathrm{CP}}\}$

$$\boxed{V_R^{\ell} = ?}$$

LR symmetry does not predict $V_L^{(\ell)}$ by itself.

It asks whether a given LH flavour structure has a RH counterpart.

U_{PMNS} is input; V_R^{ℓ} is the LR question.

Oscillation precision becomes input for right-handed flavour.

Parity as a reconstruction principle

$$G_{LR} = SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

Pati, Salam,
Mohapatra, Senjanović

Generalized $\mathcal{P}$: $x = -x$, $L \leftrightarrow R$

$$q_L \leftrightarrow q_R, \quad \ell_L \leftrightarrow \ell_R \quad \Rightarrow \quad \boxed{Y = Y^\dagger}$$

Parity not only a symmetry restoration, it is a flavour constraint

$\mathcal{P}$ relates hidden RH flavour to measured LH flavour.

Two LR neutrino branches

Majorana LR

Δ_R (triplet), $N_i = N_i^c$, $\nu_i = \nu_i^c$

$\Delta L = 2$

$0\nu\beta\beta$, $W_R \to \ell N \to \ell\ell jj$

strong LNV/LFV probes

Dirac LR

χ_R (doublet), $\nu_i \neq \nu_i^c$

$\Delta L = 0$

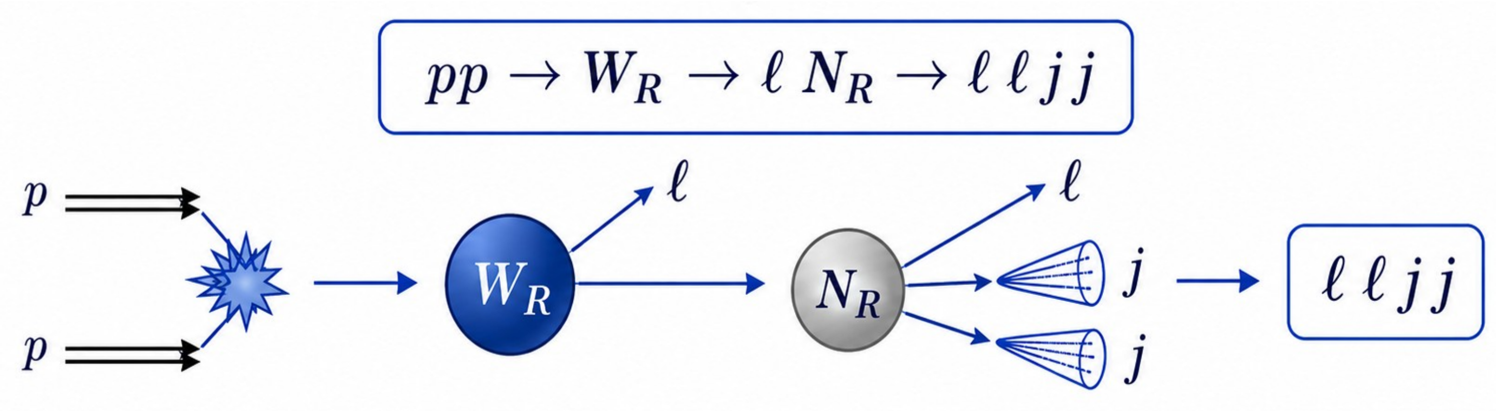
$W_R \to \ell\nu_R \Rightarrow \not{E}$

weak LFV probes

Majorana is loud. Dirac is quiet.

But quiet does not mean empty.

The classic LR signal: Keung-Senjanovic



- Direct production of WR
- Production of right-handed neutrinos
- Lepton number violation: Same-sign dileptons
- Classic LOUD Left-right signal

Keung & Senjanović, PRL 1983

Majorana LR branch

KS at LHC

$$pp \to W_R \to \ell_\alpha N_i \to \ell_\alpha \ell_\beta jj$$

$$W_R \to \ell_\alpha N_i \propto \left|(V_R^\ell)_{\alpha i}\right|^2$$

$0\nu\beta\beta$

$$(A, Z) \to (A, Z+2) + 2e^-$$

$$\mathcal{A}_{RR} \sim \left(\frac{M_W}{M_{W_R}}\right)^4 \sum_i \frac{(V_R^\ell)^2_{ei}}{m_{N_i}}$$

LFV

$$\mu \to e\gamma$$

$$\mu \to 3e$$

$$\mu^- \mathcal{N} \to e^- \mathcal{N}$$

flavour off-diagonal probes

Majorana LR: the same RH leptonic sector links collider LNV, $0\nu\beta\beta$, and LFV.

Dirac neutrinos remove the usual LNV probes

Dirac LR: what disappears

$0\nu\beta\beta$	absent
same-sign $\ell\ell jj$	absent
$W_R \to \ell\nu_R$	$\not{E}$
$\Delta L = 2$ signals	absent

V_R^ℓ hard to access directly

Where is the physics? In the parity consistency conditions.

Tiny Dirac masses meet Hermitian bidoublet Yukawas

Parity ties M_ν and M_e

$$\langle\Phi\rangle = v\begin{pmatrix}\cos\beta & 0\\ 0 & \sin\beta\, e^{i\alpha}\end{pmatrix}, \qquad Y_{1,2}^{(\ell)} = Y_{1,2}^{(\ell)\dagger}$$

$$\boxed{\begin{aligned} M_\nu &= v\left(Y_1^{(\ell)}\cos\beta + Y_2^{(\ell)}\sin\beta\, e^{-i\alpha}\right)\\ M_e &= v\left(Y_1^{(\ell)}\sin\beta\, e^{i\alpha} + Y_2^{(\ell)}\cos\beta\right)\end{aligned}}$$

$$\epsilon \equiv \sin\alpha\,\tan 2\beta$$

$$\boxed{\begin{aligned} M_\nu - M_\nu^\dagger &= i\epsilon\left(e^{i\alpha}\tan\beta\, M_\nu - M_e\right)\\ M_e - M_e^\dagger &= i\epsilon\left(M_\nu - e^{-i\alpha}\tan\beta\, M_e\right)\end{aligned}}$$

$$\boxed{m_\nu \ll m_\ell \quad \Rightarrow \quad \text{small neutrino masses become a consistency condition}}$$

Can parity reconstruct V_R^ℓ?

$$\mathcal{L}_{CC}^\ell = \overline{\ell_L}\gamma^\mu V_L^\ell \nu_L\, W_{L\mu} + \overline{\ell_R}\gamma^\mu V_R^\ell \nu_R\, W_{R\mu} + \text{h.c.}$$

$$V_L^\ell \simeq U_{\text{PMNS}} \qquad \Rightarrow \qquad \boxed{V_R^\ell = ?}$$

Oscillation data become input for the RH leptonic sector.

No loud LNV, but V_R^ℓ controls $W_R \longrightarrow \ell_\alpha \nu_{Ri}$ flavour.

A nonlinear equation determines the RH leptonic matrix

Reconstructing V_R^ℓ from parity

Input

$V_L^\ell \simeq U_{\mathrm{PMNS}}$

$m_\nu, \quad m_e, \quad \epsilon$

Master equation

$$\boxed{X^2 = m_\nu^2 + i\epsilon H X}$$

$$H \equiv V_L^{\ell\dagger} \hat{m}_e V_L^\ell$$

Output

$V_R^\ell = V_L^\ell X \hat{m}_\nu^{-1}$

ϵ domain

enhanced branches

$\epsilon = \sin\alpha \tan 2\beta, \qquad S_e = 1$ shown for simplicity

Solving the master equation reconstructs V_R^ℓ.

Tiny Dirac masses restrict parity breaking

Physical solutions restrict parity breaking

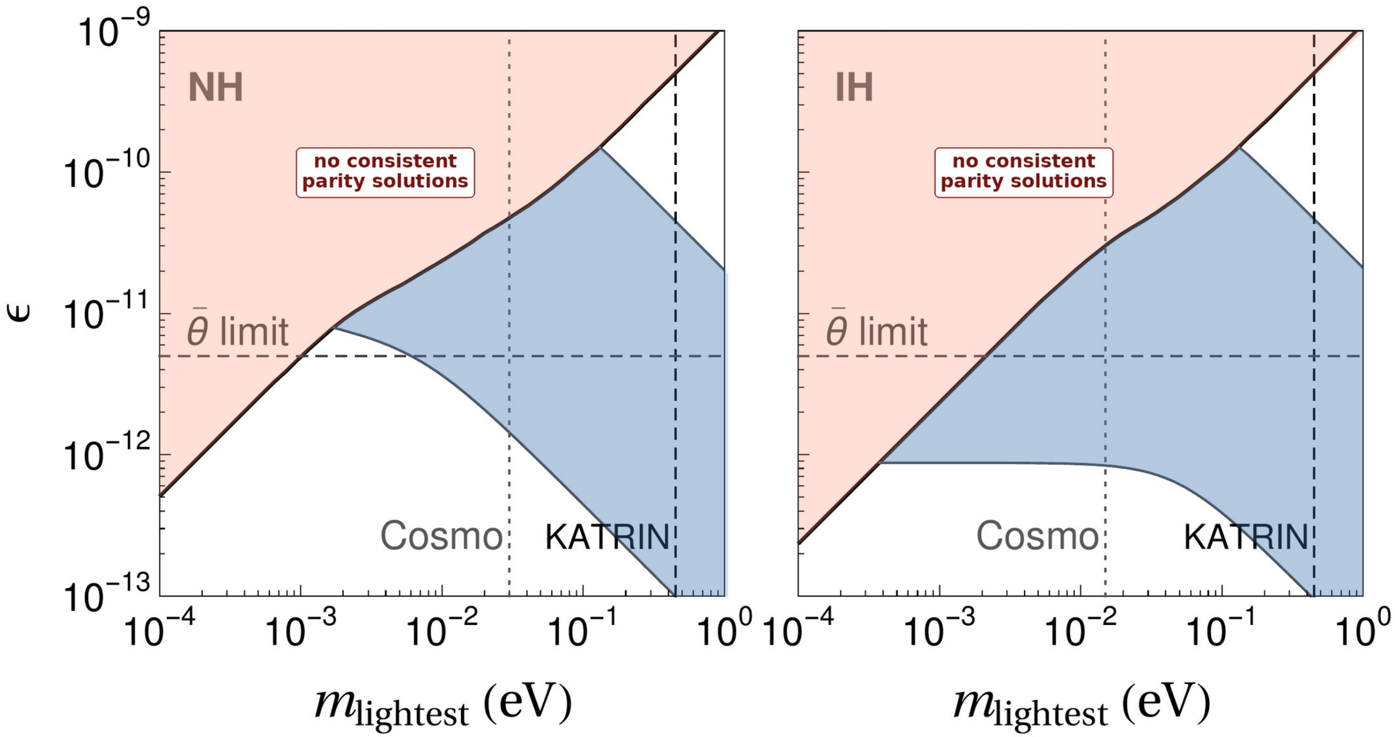
$$\boxed{X^2 = m_\nu^2 + i\epsilon H X} \qquad \text{with} \qquad U_\nu = X m_\nu^{-1} \text{ unitary}$$

$$\Rightarrow \qquad U_\nu m_\nu - m_\nu U_\nu^\dagger = i\epsilon H$$

$$m_\nu \ll m_\ell \qquad \Rightarrow \qquad \boxed{|\epsilon| \lesssim \epsilon_{\text{max}} \sim \frac{m_{\nu\ \text{scale}}}{m_\tau}}$$

Not every parity-breaking vacuum gives physical Dirac leptons.

But small parity breaking can be amplified



$$\boxed{|\epsilon| < \epsilon_{\max}(m_{\text{lightest}})}$$

Physical solutions exist only below the consistency boundary.

Most of the region: $V_R^\ell \simeq V_L^\ell$.

Localized band: small ϵ gives sizeable misalignment.

$$\boxed{m_{\text{lightest}} \text{ controls how much parity breaking is allowed.}}$$

Small ϵ does not always mean small misalignment

$$\boxed{\delta\theta_{12} \equiv |\theta^L_{12} - \theta^R_{12}| \sim \epsilon\, \frac{|H_{12}|}{|s_1 m_1 + s_2 m_2|}}$$

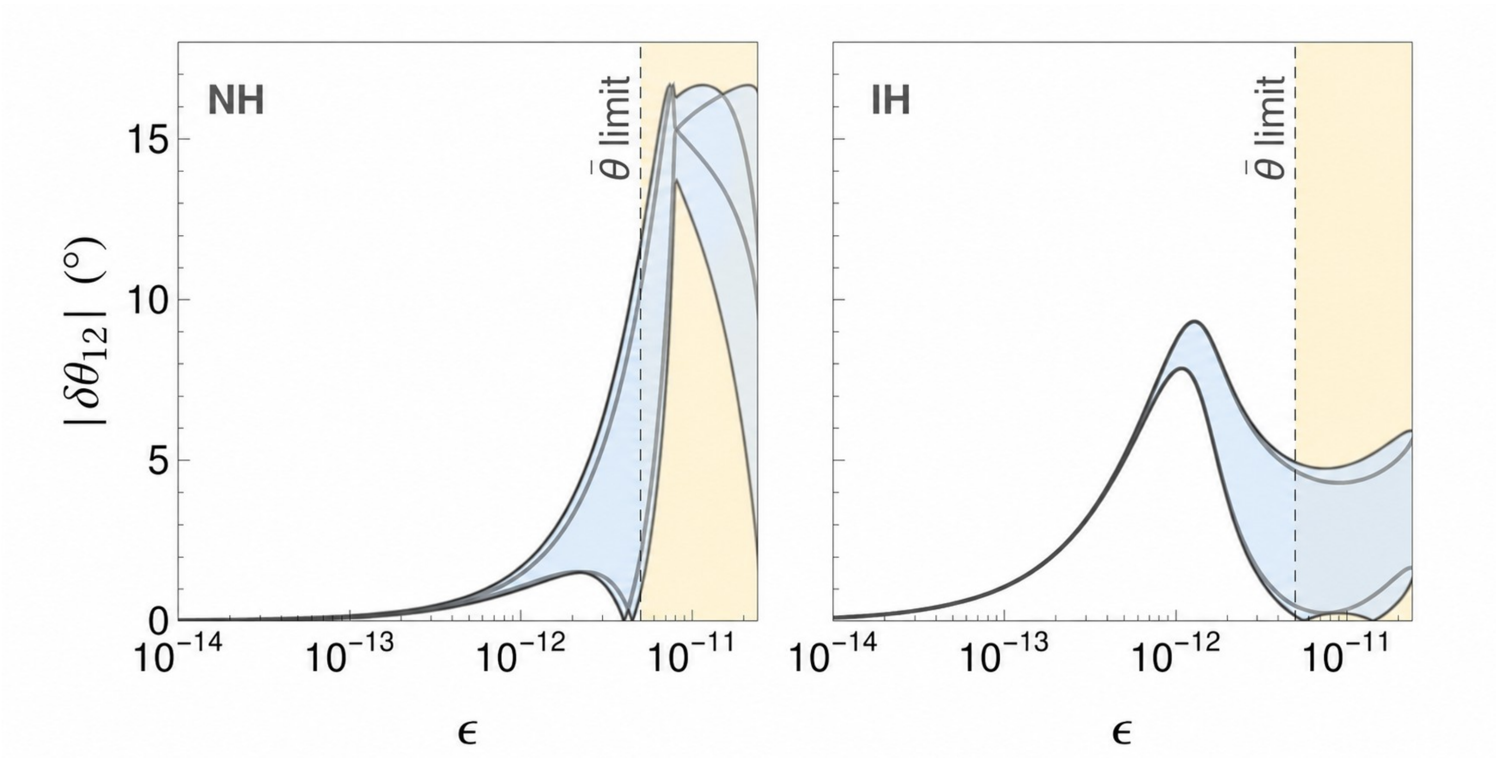
$$s_1 = s_2 \quad \Rightarrow \quad m_1 + m_2$$

$$s_1 = -s_2 \quad \Rightarrow \quad |m_1 - m_2|$$

small denominator ⇒ enhanced RH–LH misalignment

Enhancement comes from branch-dependent small denominators.

Localized enhancement of V_R^ℓ



Large RH–LH misalignment can occur inside the small-ϵ region.

Enhancement can overlap the strong-CP/EDM-selected region.

The same parameter controls induced strong CP

Experimental anchor

$$\mathcal{L}_{\rm QCD} \supset \frac{\bar\theta g_s^2}{32\pi^2} G^a_{\mu\nu}\widetilde{G}^{a\mu\nu}$$

$$d_n(\bar\theta) \sim 10^{-16}\,\bar\theta\; e\,\mathrm{cm}$$

$$|d_n| < 1.8\times 10^{-26}\; e\,\mathrm{cm}$$

$$\Rightarrow \quad |\bar\theta| \lesssim 10^{-10}$$

LR/Dirac consequence

$$\bar\theta_{\rm ind} \sim \frac{m_t}{2m_b}\epsilon$$

$$|\epsilon| \lesssim \epsilon_{\max} \sim \frac{m_\nu}{m_\tau}$$

$$\boxed{|\bar\theta|_{\max} \sim \frac{m_t}{2m_b}\epsilon_{\max} \sim \mathcal{O}\left(\frac{m_t}{m_b}\frac{m_\nu}{m_\tau}\right)}$$

$$|\bar\theta|_{\max} \sim 10^{-11}\text{–}10^{-9}$$

(for cosmologically relevant $m_{\rm lightest}$)

Dirac-neutrino smallness bounds the parameter that induces $\bar\theta$.

What does $m_\nu \ll m_\ell$ mean once parity is imposed?

Majorana LR

m_ν small $\Rightarrow$ hidden heavy sector

parity + seesaw consistency

$\Rightarrow M_D$ reconstruction

Dirac LR

m_ν small $\Rightarrow$ tiny parity-breaking window

parity + Dirac consistency

$\Rightarrow V_R^\ell,\ \epsilon_{\max}$

$$m_\nu \ll m_\ell \quad \Rightarrow \quad |\epsilon| \lesssim \epsilon_{\max} \sim \frac{m_\nu}{m_\tau}$$

$$\Rightarrow \quad |\bar{\theta}|_{\max} \sim \frac{m_t}{2m_b}\,\epsilon_{\max} \sim \mathcal{O}\left(\frac{m_t}{m_b}\frac{m_\nu}{m_\tau}\right)$$

The Dirac branch is quiet experimentally,

but remembers parity through flavour and strong CP.

Thank you

Backup slides

Same symmetry, different predictions

Majorana LR

Δ_R (triplet), $\quad N_i = N_i^c, \quad \Delta L = 2$

$0\nu\beta\beta, \qquad W_R \to \ell N \to \ell\ell jj$

$\mu \to e\gamma, \quad \mu \to 3e, \quad \mu - e$

$$\boxed{\mathcal{P}: \; M_D \text{ reconstructed from seesaw}}$$

loud, connected, strongly constrained

Dirac LR

χ_R (doublet), $\quad \nu_i \neq \nu_i^c, \quad \Delta L = 0$

$0\nu\beta\beta$: absent

$W_R \to \ell \nu_R \Rightarrow \not{E}$

$$\boxed{\mathcal{P}: \; V_R^{\ell}, \quad \epsilon_{\max}, \quad \bar{\theta}_{\max}}$$

quiet, but predictive

In both branches, $\mathcal{P}$ also predicts $V_R^q \simeq V_L^q$.

Majorana tests the seesaw; Dirac tests parity through flavour and strong CP.

What is predicted, what is not

Predicted / constrained	**Not claimed**
V_R^ℓ	direct collider observability
$\epsilon_{\max}$	dynamical vacuum selection
$\bar{\theta}_{\max}$ envelope	PQ-like solution
enhancement bands	generic large misalignment

This is a structural constraint, not a dynamical solution of strong CP.

How stable is the Dirac benchmark?

χ_R doublet $\Longrightarrow$ no renormalizable Majorana mass

$$\frac{1}{\Lambda}(L_R \chi_R)^2 \quad \Longrightarrow \quad M_R \sim \frac{v_R^2}{\Lambda}$$

$\boxed{\text{Minimal renormalizable LR is Dirac; exact Diracness may require an extra symmetry}}$

Theta bar

$$\mathcal{L}_{\bar\theta} = \bar\theta \frac{\alpha_s}{8\pi} G^a_{\mu\nu} \widetilde{G}^{a\mu\nu} \qquad |d_n| \lesssim 10^{-26}\ e\,\mathrm{cm}$$

$$d_n \sim 10^{-16}\ \bar\theta\ e\,\mathrm{cm} \qquad \boxed{|\bar\theta| \lesssim 10^{-10}}$$

$$\boxed{\bar\theta = \theta_{\mathrm{QCD}} + \arg\det(M_u M_d)}$$

$$\mathcal{P}\ \text{exact} \ \Rightarrow\ \theta_{\mathrm{QCD}} = 0$$

$$\mathcal{P}\ \text{broken} \ \Rightarrow\ \bar\theta \simeq \arg\det(M_u M_d)$$

VR expansions

$$(V_R^{(\ell)})_{ij} = s_{e_i}(V_L^{(\ell)})_{ik}\left[\delta_{kj} + i\epsilon\frac{H_{kj}}{\hat{m}_{\nu_k} + \hat{m}_{\nu_j}}\right] s_{\nu_j} + \mathcal{O}(\epsilon^2),$$

$$\delta\theta_{12} \simeq -\epsilon\,\frac{\Im H_{12}}{\hat{m}_{\nu_1} + \hat{m}_{\nu_2}}$$

Small-epsilon expansion

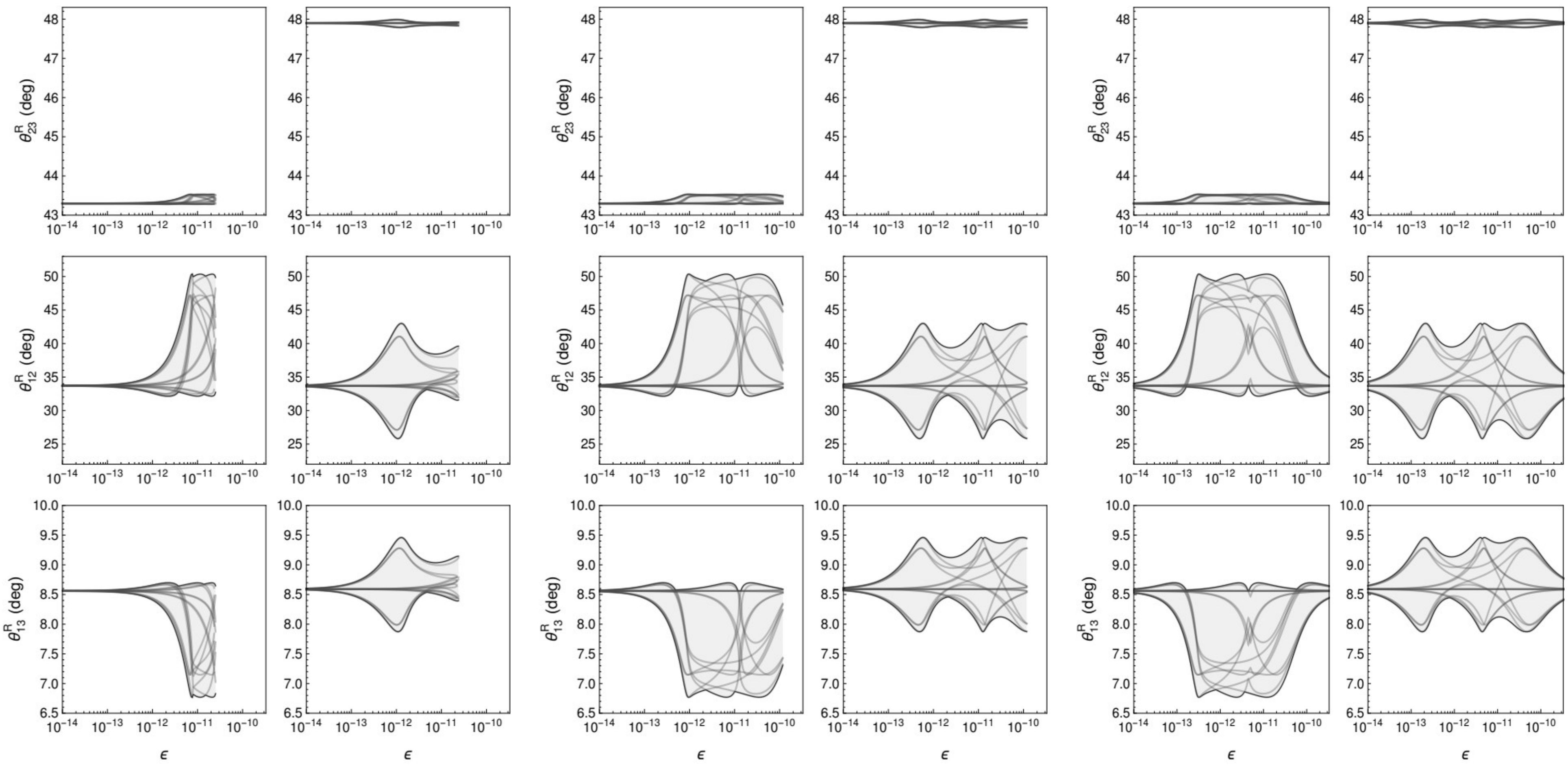
$$\begin{aligned}(V_R^{(\ell)})_{ij} =& s_{e_i}\left[e^{i\phi_i}\,\delta_{ik} + \frac{\left(V_L^{(\ell)}\,\frac{\Delta m_\nu^2}{m_0^2}\,V_L^{(\ell)\dagger}\right)_{ik}}{e^{-i\phi_i} + e^{i\phi_k}}\right](V_L^{(\ell)})_{kj} \\ & -\frac{1}{2}s_{e_i}\,e^{i\phi_i}\left(V_L^{(\ell)}\frac{\Delta m_\nu^2}{m_0^2}\right)_{ij} + \mathcal{O}\left(\frac{\Delta m_\nu^4}{m_0^4}\right)\end{aligned}$$

$$\delta\theta_{12} \simeq 2s_{\nu_1}\,\frac{c_{23}^L}{c_{13}^L}\,\frac{\Im\left[\left(V_L^{(\ell)}\Delta m_\nu^2\,V_L^{(\ell)\dagger}\right)_{12}\right]}{\epsilon\, m_0\,(\hat{m}_\mu - \hat{m}_e)}$$

$$e^{i\phi_i} = s_{\nu_i}\sqrt{1 - \epsilon^2\frac{\hat{m}_{e_i}^2}{4m_0^2}} + i\,\epsilon\,\frac{\hat{m}_{e_i}}{2m_0}, \qquad s_{\nu_i} = \pm 1.$$

Quasi-degenerate expansion

Angles - mass grid

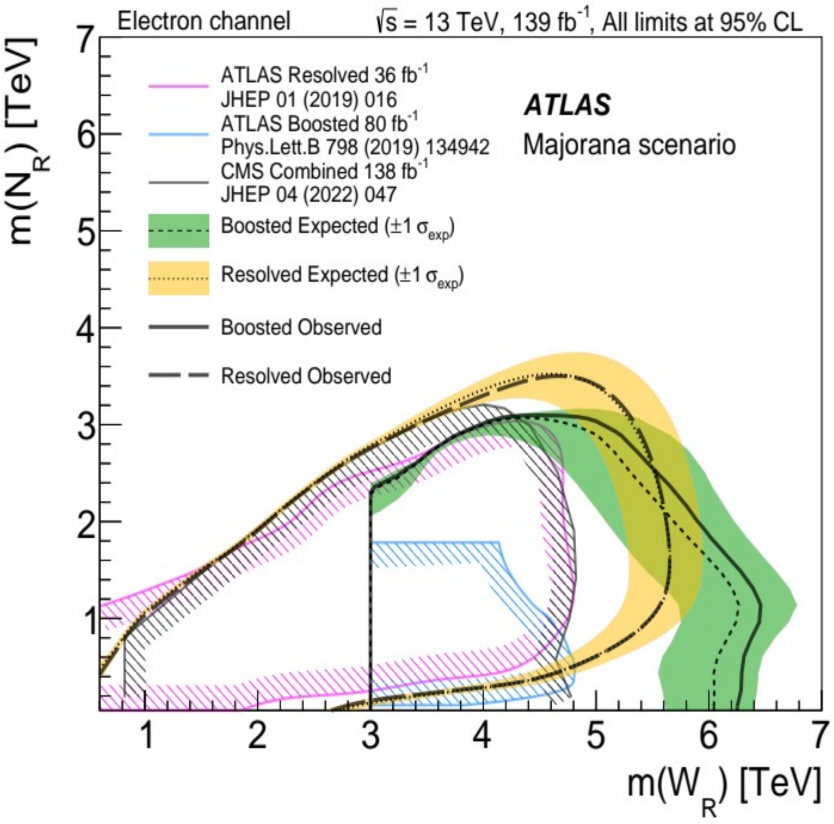


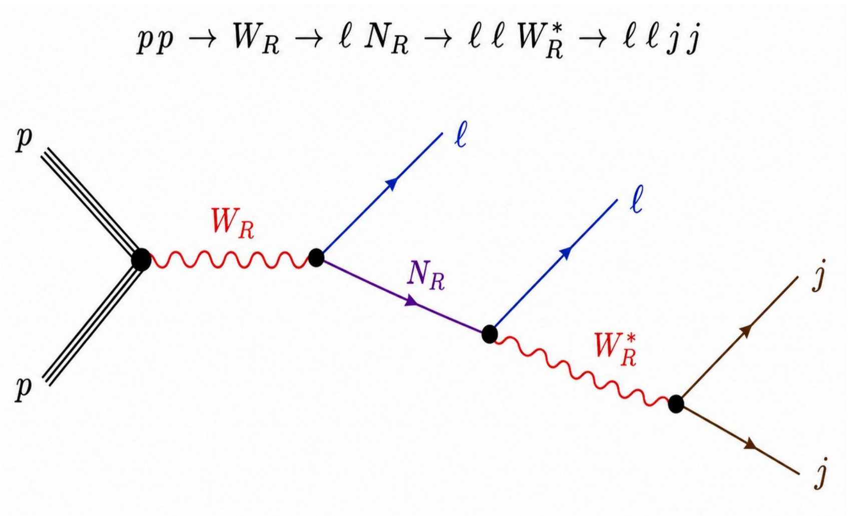
As m_{lightest} grows, the spectrum compresses and the enhancement widens.

$\theta_R - \theta_L$ is signed: large positive or negative values both mean large RH–LH misalignment.

The classic LR signal: Keung-Senjanovic

ATLAS exclusions





- WR up to 6.4 TeV
- N reach up to 3.5 TeV in favorable regions

ATLAS, 13 TeV, 139 fb^{-1} (2023)

Selected references

Foundations of LR parity:

Pati–Salam; Mohapatra–Pati; Senjanović–Mohapatra

Majorana LR and LNV probes:

Mohapatra–Senjanović 1980; Keung–Senjanović 1983;
Maiezza–Nemevšek–Nesti–Senjanović 2010;
Tello et al. 2011; Nemevšek–Senjanović–Tello 2013;
Senjanović–Tello 2017, 2019

Dirac neutrinos in LR:

Branco–Senjanović 1978; Tello PRD 113, 115060 (2026)

RH flavour and strong CP:

Zhang–An–Ji–Mohapatra 2008; Senjanović–Tello 2015;
Maiezza–Nemevšek 2014; Bertolini–Maiezza–Nesti 2020

Experiments:

Abel et al. 2020; ATLAS 2023