

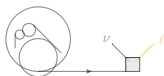
Testing ν Mass Models at Colliders

Astrophysical Seminar, IFJ PAN

Richard Ruiz

Institute of Nuclear Physics – Polish Academy of Science (IFJ PAN)

2 October 2026



many thanks for the invitation!

big idea: What can collider experiments say about the origin of neutrino masses?

a lot. for extensive reviews, see Cai, et al [[1706.08524](#)] and Cai, et al [[1711.02180](#)]

outline

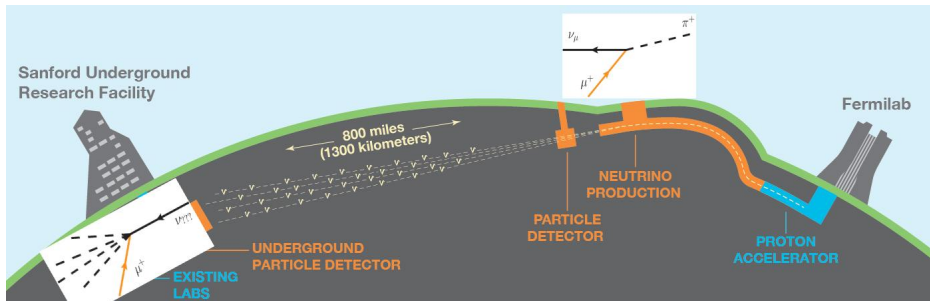
- neutrino masses and neutrino oscillations for non-experts
- three problems of nonzero neutrino masses
- proposed solutions and proposed tests

important: We have 30'+15'. Questions are welcome at any time!

(especially from students and jr postdocs!)

part 1: neutrino oscillations and neutrino masses

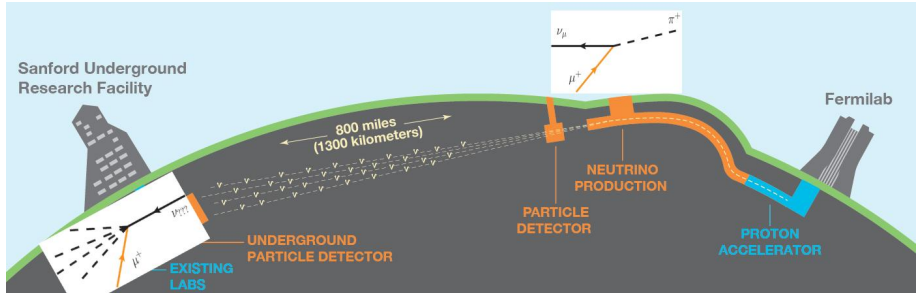
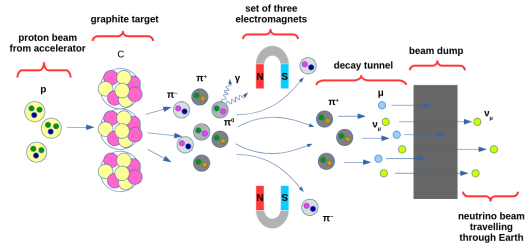
Idea: count ν_μ at near detector and compare to # at far detector



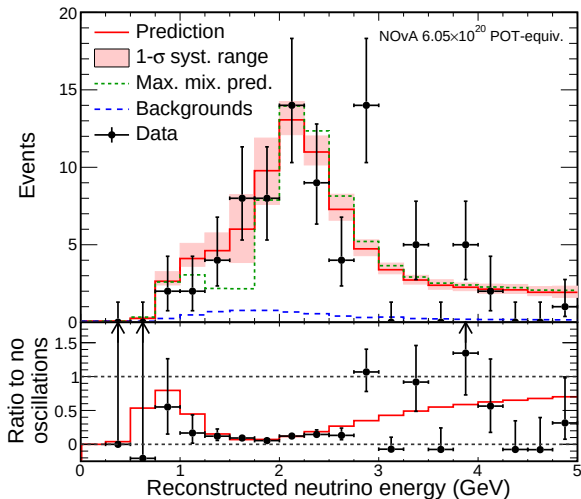
“accelerator ν 's” are
tertiary/3rd-stage beams
with good $\nu_\mu, \bar{\nu}_\mu$ purity



Lederman, Schwartz, Steinberger (PRL'62) 🏆 ('88)



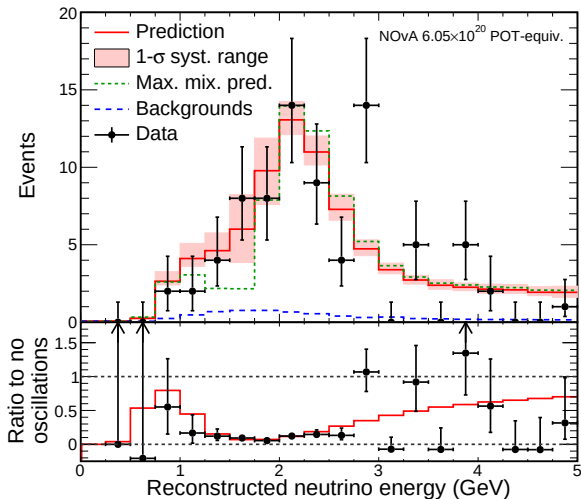
Result: far detector reports ν_μ deficit + unexpected appearance of ν_e/ν_τ
(focus on the lower panel!)



Interpretation: neutrinos are transitioning between **flavor eigenstates** and **mass eigenstates**:

$$\nu_{\ell_1} \rightarrow \nu_{\text{mass}} \rightarrow \nu_{\ell_2}$$

Result: far detector reports ν_μ deficit + unexpected appearance of ν_e/ν_τ
(focus on the lower panel!)



Interpretation: neutrinos are transitioning between **flavor eigenstates** and **mass eigenstates**:

$$\nu_{l_1} \rightarrow \nu_{\text{mass}} \rightarrow \nu_{l_2}$$

evidence for ν masses!



('15) SNO, Super-K

the massive ν hypothesis
(one slide for particle folks)

Consider left-handed (LH), $SU(2)_L$ lepton doublets (**gauge eigenbasis**):

$$L_{aL} = \begin{pmatrix} \nu_a \\ l_a \end{pmatrix}_L, \quad a = 1, 2, 3.$$

Consider left-handed (LH), $SU(2)_L$ lepton doublets (**gauge eigenbasis**):

$$L_{aL} = \begin{pmatrix} \nu_a \\ l_a \end{pmatrix}_L, \quad a = 1, 2, 3.$$

The Lagrangian for $W^\pm$ coupling to **leptons** in the **flavor eigenbasis** is

$$\mathcal{L}_{CC} = -\frac{g}{\sqrt{2}} W_\mu^\pm \sum_{l=1}^3 [\overline{\nu_{lL}} \gamma^\mu P_L l] + \text{H.c.}$$

Consider left-handed (LH), $SU(2)_L$ lepton doublets (**gauge eigenbasis**):

$$L_{aL} = \begin{pmatrix} \nu_a \\ l_a \end{pmatrix}_L, \quad a = 1, 2, 3.$$

The Lagrangian for $W^\pm$ coupling to **leptons** in the **flavor eigenbasis** is

$$\mathcal{L}_{CC} = -\frac{g}{\sqrt{2}} W_\mu^+ \sum_{l=1}^3 [\overline{\nu_{lL}} \gamma^\mu P_L l] + \text{H.c.}$$

Supposing $m_\nu \neq 0$, we can rotate ν_l and l into the **mass eigenbasis**:

$$\nu_l = \sum_{m=1}^3 \Omega_{lm} \nu_m \quad \text{and} \quad l = \sum_{\ell=1}^3 \Omega_{l\ell} \ell$$

Consider left-handed (LH), $SU(2)_L$ lepton doublets (**gauge eigenbasis**):

$$L_{aL} = \begin{pmatrix} \nu_a \\ l_a \end{pmatrix}_L, \quad a = 1, 2, 3.$$

The Lagrangian for $W^\pm$ coupling to **leptons** in the **flavor eigenbasis** is

$$\mathcal{L}_{CC} = -\frac{g}{\sqrt{2}} W_\mu^+ \sum_{l=1}^3 [\overline{\nu_{lL}} \gamma^\mu P_L l^-] + \text{H.c.}$$

Supposing $m_\nu \neq 0$, we can rotate ν_l and l into the **mass eigenbasis**:

$$\nu_l = \sum_{m=1}^3 \Omega_{lm} \nu_m \quad \text{and} \quad l = \sum_{\ell=1}^3 \Omega_{l\ell} \ell$$

This allows us to describe SM $W^\pm$ boson coupling to ν *with* $m_\nu \neq 0$:

$$\mathcal{L}_{CC} = -\frac{g}{\sqrt{2}} W_\mu^+ \sum_{\ell=e}^3 \sum_{m=1}^3 [\overline{\nu_m} \underbrace{U_{m\ell}^*}_{U_{m\ell}^* \equiv \sum_l \Omega_{ml}^* \Omega_{l\ell}} \gamma^\mu P_L \ell^-] + \text{H.c.}$$

Consider left-handed (LH), $SU(2)_L$ lepton doublets (**gauge eigenbasis**):

$$L_{aL} = \begin{pmatrix} \nu_a \\ l_a \end{pmatrix}_L, \quad a = 1, 2, 3.$$

The Lagrangian for $W^\pm$ coupling to **leptons** in the **flavor eigenbasis** is

$$\mathcal{L}_{CC} = -\frac{g}{\sqrt{2}} W_\mu^\pm \sum_{l=1}^3 [\overline{\nu_{lL}} \gamma^\mu P_L l] + \text{H.c.}$$

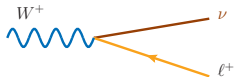
Supposing $m_\nu \neq 0$, we can rotate ν_l and l into the **mass eigenbasis**:

$$\nu_l = \sum_{m=1}^3 \Omega_{lm} \nu_m \quad \text{and} \quad l = \sum_{\ell=1}^3 \Omega_{l\ell} \ell$$

This allows us to describe SM $W^\pm$ boson coupling to ν *with* $m_\nu \neq 0$:

$$\mathcal{L}_{CC} = -\frac{g}{\sqrt{2}} W_\mu^\pm \sum_{\ell=e}^3 \sum_{m=1}^3 [\overline{\nu_m} \underbrace{U_{m\ell}^*}_{U_{m\ell}^* \equiv \sum_l \Omega_{ml}^* \Omega_{l\ell}} \gamma^\mu P_L \ell] + \text{H.c.}$$

Standard Model (SM) interaction are modified by **PMNS** mixing factor:



$$\Gamma^\mu = \frac{-ig}{\sqrt{2}} \gamma^\mu P_L \rightarrow \tilde{\Gamma}^\mu = \frac{-ig}{\sqrt{2}} U_{m\ell}^* \gamma^\mu P_L$$

ν oscillations

(an exercise in undergraduate quantum mechanics)

2-State Neutrino Mixing

Generically, mixing between **flavor eigenstates** and **mass eigenstates** is given by **unitary transformation/rotation**

$$\underbrace{\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}}_{\text{flavor basis}} = \underbrace{\begin{pmatrix} U_{e1} & U_{e2} \\ U_{\mu 1} & U_{\mu 2} \end{pmatrix}}_{\text{mixing}} \underbrace{\begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}}_{\text{mass basis}} = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

2-State Neutrino Mixing

Generically, mixing between **flavor eigenstates** and **mass eigenstates** is given by **unitary transformation/rotation**

$$\underbrace{\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}}_{\text{flavor basis}} = \underbrace{\begin{pmatrix} U_{e1} & U_{e2} \\ U_{\mu1} & U_{\mu2} \end{pmatrix}}_{\text{mixing}} \underbrace{\begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}}_{\text{mass basis}} = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

For a **two-state system**, the state vector for ν_ℓ ($\ell = e, \mu$) is simply

$$\underbrace{|\nu_e\rangle}_{\text{flavor basis}} = U_{e1} \underbrace{|\nu_1\rangle}_{\text{light}} + U_{e2} \underbrace{|\nu_2\rangle}_{\text{heavy}} = \cos \theta |\nu_1\rangle + \sin \theta |\nu_2\rangle$$

2-State Neutrino Mixing

Generically, mixing between **flavor eigenstates** and **mass eigenstates** is given by **unitary transformation/rotation**

$$\underbrace{\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}}_{\text{flavor basis}} = \underbrace{\begin{pmatrix} U_{e1} & U_{e2} \\ U_{\mu 1} & U_{\mu 2} \end{pmatrix}}_{\text{mixing}} \underbrace{\begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}}_{\text{mass basis}} = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

For a **two-state system**, the state vector for ν_ℓ ($\ell = e, \mu$) is simply

$$\underbrace{|\nu_e\rangle}_{\text{flavor basis}} = U_{e1} \underbrace{|\nu_1\rangle}_{\text{light}} + U_{e2} \underbrace{|\nu_2\rangle}_{\text{heavy}} = \cos \theta |\nu_1\rangle + \sin \theta |\nu_2\rangle$$

If we treat the spacetime propagation of ν_m ($m = 1, 2$) as a plane wave, then the **evolution** from $x^\mu = x_a^\mu$ to $x^\mu = x_b^\mu$ is

$$|\nu_\ell(x_b, x_a)\rangle = U_\ell(x_b, x_a) |\nu_\ell\rangle = U_{\ell 1} U_1(x_b, x_a) |\nu_1\rangle + U_{\ell 2} U_2(x_b, x_a) |\nu_2\rangle$$

Evolution through space and time

Assuming $\hat{p}_\nu = \Delta \hat{x}$, the plane wave evolution over $L = |\vec{x}_b - \vec{x}_a|$ is

$$U_m(x_b, x_a) = e^{-ip_m \cdot (x_b - x_a)}$$

Evolution through space and time

Assuming $\hat{p}_\nu = \Delta\hat{x}$, the plane wave evolution over $L = |\vec{x}_b - \vec{x}_a|$ is

$$U_m(x_b, x_a) = e^{-ip_m \cdot (x_b - x_a)} = e^{-i(E_m \Delta t_m - \vec{p}_m \cdot (\vec{x}_b - \vec{x}_a))}$$

Evolution through space and time

Assuming $\hat{p}_\nu = \Delta\hat{x}$, the plane wave evolution over $L = |\vec{x}_b - \vec{x}_a|$ is

$$U_m(x_b, x_a) = e^{-ip_m \cdot (x_b - x_a)} = e^{-i(E_m \Delta t_m - \vec{p}_m \cdot (\vec{x}_b - \vec{x}_a))} \approx e^{-i(E_m \Delta t_m - |\vec{p}_m| L_m)}$$

Evolution through space and time

Assuming $\hat{p}_\nu = \Delta \hat{x}$, the plane wave evolution over $L = |\vec{x}_b - \vec{x}_a|$ is

$$U_m(x_b, x_a) = e^{-ip_m \cdot (x_b - x_a)} = e^{-i(E_m \Delta t_m - \vec{p}_m \cdot (\vec{x}_b - \vec{x}_a))} \approx e^{-i(E_m \Delta t_m - |\vec{p}_m| L)}$$

Now, working in the ultra relativistic limit, where $E_m + |\vec{p}_m| \approx 2E_m$,

$$(E_m \Delta t_m - |\vec{p}_m| L) \approx (E_m - |\vec{p}_m|) L$$

Evolution through space and time

Assuming $\hat{p}_\nu = \Delta \hat{x}$, the plane wave evolution over $L = |\vec{x}_b - \vec{x}_a|$ is

$$U_m(x_b, x_a) = e^{-ip_m \cdot (x_b - x_a)} = e^{-i(E_m \Delta t_m - \vec{p}_m \cdot (\vec{x}_b - \vec{x}_a))} \approx e^{-i(E_m \Delta t_m - |\vec{p}_m| L_m)}$$

Now, working in the ultra relativistic limit, where $E_m + |\vec{p}_m| \approx 2E_m$,

$$(E_m \Delta t_m - |\vec{p}_m| L) \approx (E_m - |\vec{p}_m|) L = \left(\frac{E_m^2 - |\vec{p}_m|^2}{E_m + |\vec{p}_m|} \right) L \approx \left(\frac{m_m^2}{2E_m} \right) L$$

Evolution through space and time

Assuming $\hat{p}_\nu = \Delta \hat{x}$, the plane wave evolution over $L = |\vec{x}_b - \vec{x}_a|$ is

$$U_m(x_b, x_a) = e^{-ip_m \cdot (x_b - x_a)} = e^{-i(E_m \Delta t_m - \vec{p}_m \cdot (\vec{x}_b - \vec{x}_a))} \approx e^{-i(E_m \Delta t_m - |\vec{p}_m| L_m)}$$

Now, working in the ultra relativistic limit, where $E_m + |\vec{p}_m| \approx 2E_m$,

$$(E_m \Delta t_m - |\vec{p}_m| L) \approx (E_m - |\vec{p}_m|) L = \left(\frac{E_m^2 - |\vec{p}_m|^2}{E_m + |\vec{p}_m|} \right) L \approx \left(\frac{m_m^2}{2E_m} \right) L$$

Since $m_2, m_1 \ll E_1, E_2$, the E_m can be approximated as the same:

$$|\nu_e(E, L)\rangle = U_{e1} e^{-im_1^2 L/2E} |\nu_1\rangle + U_{e2} e^{-im_2^2 L/2E} |\nu_2\rangle$$

$$|\nu_\mu(E, L)\rangle = U_{\mu1} e^{-im_1^2 L/2E} |\nu_1\rangle + U_{\mu2} e^{-im_2^2 L/2E} |\nu_2\rangle$$

We are now ready to compute **oscillation transtions**!

Neutrino Oscillation Transitions

To reproduce the ν_μ deficit, consider the $\nu_\mu \rightarrow \nu_\mu$ *transition amplitude*:

$$\mathcal{M}(\nu_\mu \rightarrow \nu_\mu) \equiv \langle \nu_\mu | \nu_\mu(E, L) \rangle$$

Neutrino Oscillation Transitions

To reproduce the ν_μ deficit, consider the $\nu_\mu \rightarrow \nu_\mu$ *transition amplitude*:

$$\begin{aligned}\mathcal{M}(\nu_\mu \rightarrow \nu_\mu) &\equiv \langle \nu_\mu | \nu_\mu(E, L) \rangle \\ &= \underbrace{\left[\langle \nu_1 | U_{\mu 1}^* + \langle \nu_2 | U_{\mu 2}^* \right]}_{= \langle \nu_\mu |} \times \underbrace{\left[U_{\mu 1} e^{-im_1^2 L/2E} |\nu_1\rangle + U_{\mu 2} e^{-im_2^2 L/2E} |\nu_2\rangle \right]}_{= |\nu_\mu(E, L)\rangle}\end{aligned}$$

Neutrino Oscillation Transitions

To reproduce the ν_μ deficit, consider the $\nu_\mu \rightarrow \nu_\mu$ *transition amplitude*:

$$\begin{aligned}\mathcal{M}(\nu_\mu \rightarrow \nu_\mu) &\equiv \langle \nu_\mu | \nu_\mu(E, L) \rangle \\ &= \underbrace{[\langle \nu_1 | U_{\mu 1}^* + \langle \nu_2 | U_{\mu 2}^*]}_{= \langle \nu_\mu |} \times \underbrace{[U_{\mu 1} e^{-im_1^2 L/2E} |\nu_1\rangle + U_{\mu 2} e^{-im_2^2 L/2E} |\nu_2\rangle]}_{= |\nu_\mu(E, L)\rangle}\end{aligned}$$

Since $|\nu_m\rangle$ are mass **eigenstates**, $\langle \nu_{m'} | \nu_m \rangle = \delta_{m'm}$. This implies

$$\mathcal{M}(\nu_\mu \rightarrow \nu_\mu) = e^{-im_1^2 L/2E} |U_{\mu 1}|^2 \langle \nu_1 | \nu_1 \rangle + e^{-im_2^2 L/2E} |U_{\mu 2}|^2 \langle \nu_2 | \nu_2 \rangle$$

Neutrino Oscillation Transitions

To reproduce the ν_μ deficit, consider the $\nu_\mu \rightarrow \nu_\mu$ *transition amplitude*:

$$\begin{aligned}\mathcal{M}(\nu_\mu \rightarrow \nu_\mu) &\equiv \langle \nu_\mu | \nu_\mu(E, L) \rangle \\ &= \underbrace{[\langle \nu_1 | U_{\mu 1}^* + \langle \nu_2 | U_{\mu 2}^*]}_{= \langle \nu_\mu |} \times \underbrace{\left[U_{\mu 1} e^{-im_1^2 L/2E} |\nu_1\rangle + U_{\mu 2} e^{-im_2^2 L/2E} |\nu_2\rangle \right]}_{= |\nu_\mu(E, L)\rangle}\end{aligned}$$

Since $|\nu_m\rangle$ are mass **eigenstates**, $\langle \nu_{m'} | \nu_m \rangle = \delta_{m'm}$. This implies

$$\mathcal{M}(\nu_\mu \rightarrow \nu_\mu) = e^{-im_1^2 L/2E} |U_{\mu 1}|^2 \langle \nu_1 | \nu_1 \rangle + e^{-im_2^2 L/2E} |U_{\mu 2}|^2 \langle \nu_2 | \nu_2 \rangle$$

The $\nu_\mu \rightarrow \nu_\mu$ *transition probability* is

$$\begin{aligned}\text{Pr}(\nu_\mu \rightarrow \nu_\mu) &= |\mathcal{M}(\nu_\mu \rightarrow \nu_\mu)|^2 = |U_{\mu 1}|^4 + |U_{\mu 2}|^4 \\ &\quad + e^{-i\Delta m_{21}^2 L/2E} |U_{\mu 1}|^2 |U_{\mu 2}|^2 + e^{+i\Delta m_{21}^2 L/2E} |U_{\mu 1}|^2 |U_{\mu 2}|^2\end{aligned}$$

note: $\Delta m_{21}^2 \equiv (m_2^2 - m_1^2)$

Some Quick Algebra

Recalling that $U_{e1} = U_{\mu 2} = \cos \theta$ and $U_{e2} = -U_{\mu 1} = \sin \theta$,

$$\text{Pr}(\nu_{\mu} \rightarrow \nu_{\mu}) = \sin^4 \theta + \cos^4 \theta + 2 \sin^2 \theta \cos^2 \theta \cos \left[\frac{\Delta m_{21}^2 L}{2E} \right]$$

Some Quick Algebra

Recalling that $U_{e1} = U_{\mu 2} = \cos \theta$ and $U_{e2} = -U_{\mu 1} = \sin \theta$,

$$\begin{aligned}\Pr(\nu_{\mu} \rightarrow \nu_{\mu}) &= \sin^4 \theta + \cos^4 \theta + 2 \sin^2 \theta \cos^2 \theta \cos \left[\frac{\Delta m_{21}^2 L}{2E} \right] \\ &= 1 - \sin^2(2\theta) \sin^2 \left[\frac{\Delta m_{21}^2 L}{4E} \right]\end{aligned}$$

Some Quick Algebra

Recalling that $U_{e1} = U_{\mu 2} = \cos \theta$ and $U_{e2} = -U_{\mu 1} = \sin \theta$,

$$\begin{aligned}\Pr(\nu_\mu \rightarrow \nu_\mu) &= \sin^4 \theta + \cos^4 \theta + 2 \sin^2 \theta \cos^2 \theta \cos \left[\frac{\Delta m_{21}^2 L}{2E} \right] \\ &= 1 - \sin^2(2\theta) \sin^2 \left[\frac{\Delta m_{21}^2 L}{4E} \right]\end{aligned}$$

Lots to unpack:

$$\Pr(\nu_\mu \rightarrow \nu_\mu) = \underbrace{1}_{\text{unitarity}} - \underbrace{\sin^2(2\theta)}_{\text{amplitude of dip}} \underbrace{\sin^2 \left[\frac{\Delta m_{21}^2 L}{4E} \right]}_{\text{spacing between beats}}$$

Some Quick Algebra

Recalling that $U_{e1} = U_{\mu 2} = \cos \theta$ and $U_{e2} = -U_{\mu 1} = \sin \theta$,

$$\begin{aligned}\Pr(\nu_{\mu} \rightarrow \nu_{\mu}) &= \sin^4 \theta + \cos^4 \theta + 2 \sin^2 \theta \cos^2 \theta \cos \left[\frac{\Delta m_{21}^2 L}{2E} \right] \\ &= 1 - \sin^2(2\theta) \sin^2 \left[\frac{\Delta m_{21}^2 L}{4E} \right]\end{aligned}$$

Lots to unpack:

$$\Pr(\nu_{\mu} \rightarrow \nu_{\mu}) = \underbrace{1}_{\text{unitarity}} - \underbrace{\sin^2(2\theta)}_{\text{amplitude of dip}} \underbrace{\sin^2 \left[\frac{\Delta m_{21}^2 L}{4E} \right]}_{\text{spacing between beats}}$$

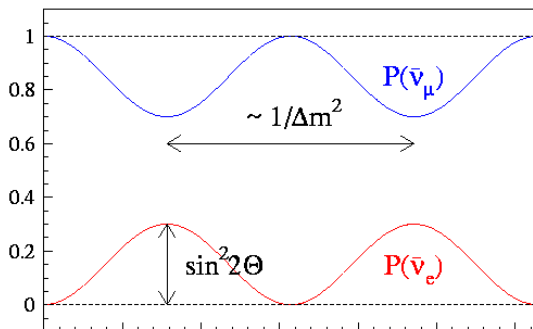
By conservation of probability $1 = \Pr(\nu_{\mu} \rightarrow \nu_{\mu}) + \Pr(\nu_{\mu} \rightarrow \nu_e)$, so the $\nu_{\mu} \rightarrow \nu_e$ *appearance probability* is

$$\Pr(\nu_{\mu} \rightarrow \nu_e) = 1 - \Pr(\nu_{\mu} \rightarrow \nu_{\mu}) = \sin^2(2\theta) \sin^2 \left[\frac{\Delta m_{21}^2 L}{4E} \right]$$

Understanding Neutrino Oscillation Plots

$$\text{Pr}(\nu_\mu \rightarrow \nu_\mu) = \underbrace{1}_{\text{unitarity}} - \underbrace{\sin^2(2\theta)}_{\text{minimum of dip}} \underbrace{\sin^2\left[\frac{\Delta m_{21}^2 L}{4E}\right]}_{\text{spacing between beats}}$$

$$\text{Pr}(\nu_\mu \rightarrow \nu_e) = \underbrace{\sin^2(2\theta)}_{\text{maximum of peak}}$$

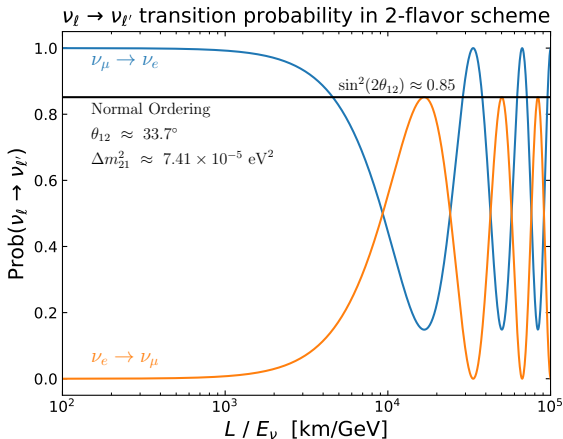


Understanding Neutrino Oscillation Plots

With updated inputs:

gitlab.cern.ch/rirui/public-projects/-/tree/master/NuPhysSandbox

$$\Pr(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta) \sin^2 \left[\frac{\Delta m_{21}^2 L}{4E} \right] \quad \Pr(\nu_\mu \rightarrow \nu_e) = \sin^2(2\theta)$$



The 3×3 Paradigm

To date, all oscillation data can be described within the 3×3 Paradigm

- 3 ν_ℓ (flavor states) $\implies$ 3 mixing angles
- 3 ν_k (mass states) $\implies$ 2 mass splittings **one may be massless!**
- 1 CP phase (if **Dirac**); +2 CP phases (if **Majorana**)

$$U_{\text{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\text{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\text{CP}}} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} e^{i\eta_1} & 0 & 0 \\ 0 & e^{i\eta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

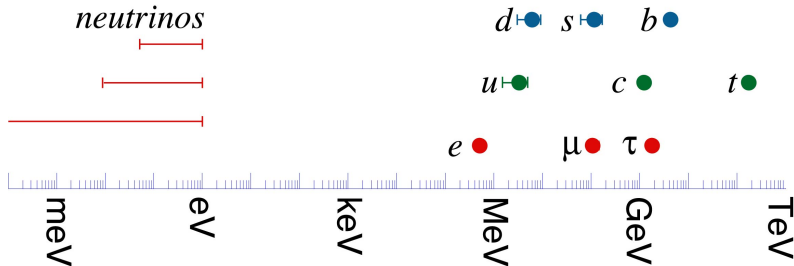
$$s_{ij} = \sin \theta_{ij}, \quad c_{ij} = \cos \theta_{ij}$$

okay, ν have mass. is this a problem?

yes

part 2: three open questions

1. The Scale Problem



Data make clear that at least two neutrinos have nonzero masses

- Searches place upper limit $m_\nu \lesssim \mathcal{O}(0.5) \text{ eV} \ll \sqrt{2}\langle\Phi_{\text{SM}}\rangle \approx 246 \text{ GeV}$

KATRIN [[2406.13516](#)]

- **The Scale Problem:** What causes m_ν to be so tiny?

2. The 1/2 Problem

In quantum field theory: we learn about three types of fermions

$$\mathcal{L}_{\text{Kin.}} = \bar{\psi} i \not{\partial} \psi \quad \mathcal{L}_{\text{Kin.}} = \bar{\psi} (i \not{\partial} - m) \psi \quad \mathcal{L}_{\text{Kin.}} = \frac{1}{2} \bar{\psi} (i \not{\partial} - m) \psi$$

Weyl fermion ($m = 0$)

Dirac fermion ($m \neq 0$)

Majorana fermion ($m \neq 0$)

2. The 1/2 Problem

In quantum field theory: we learn about three types of fermions

$$\mathcal{L}_{\text{Kin.}} = \bar{\psi} i \not{\partial} \psi \quad \mathcal{L}_{\text{Kin.}} = \bar{\psi} (i \not{\partial} - m) \psi \quad \mathcal{L}_{\text{Kin.}} = \frac{1}{2} \bar{\psi} (i \not{\partial} - m) \psi$$

Weyl fermion ($m = 0$) Dirac fermion ($m \neq 0$) Majorana fermion ($m \neq 0$)

- **History:** *Model of Leptons* (Weinberg'67) hypothesizes massless ν
(no evidence for $m_\nu \neq 0$ at the time)
- ν oscillations falsified the “Weyl hypothesis” 🏆('88)
but evidence only for $m_\nu \neq 0$, not Dirac vs Majorana
- **The 1/2 Problem:** What is the kinetic Lagrangian of ν ?

data gives no preference for **Dirac** or **Majorana** nature

the SM does provide some theoretical guidance!

$m_\nu \neq 0 \implies$ **new physics must exist**

Ma('98) + others

$m_\nu \neq 0 \implies$ **new physics must exist**

Ma('98) + others

$m_\nu \neq 0 + \text{left - handed (LH) weak currents}$

(renormalizability)

LH Majorana mass : $\frac{1}{2}m_\nu^L \overline{\nu}_L \nu_L^c$

Dirac mass : $m_\nu^D \overline{\nu}_L \nu_R$

(gauge invariance)

$m_\nu^L = y \langle \Delta \rangle$ or new dynamics

$m_\nu^D = y \langle \Phi_{\text{SM}} \rangle$

$m_\nu \neq 0 \implies$ **new physics must exist**

Ma('98) + others

$m_\nu \neq 0 + \text{left - handed (LH) weak currents}$

(renormalizability)

LH Majorana mass : $\frac{1}{2}m_\nu^L \overline{\nu}_L \nu_L^c$

Dirac mass : $m_\nu^D \overline{\nu}_L \nu_R$

(gauge invariance)

$m_\nu^L = y \langle \Delta \rangle$ or new dynamics

$m_\nu^D = y \langle \Phi_{\text{SM}} \rangle$

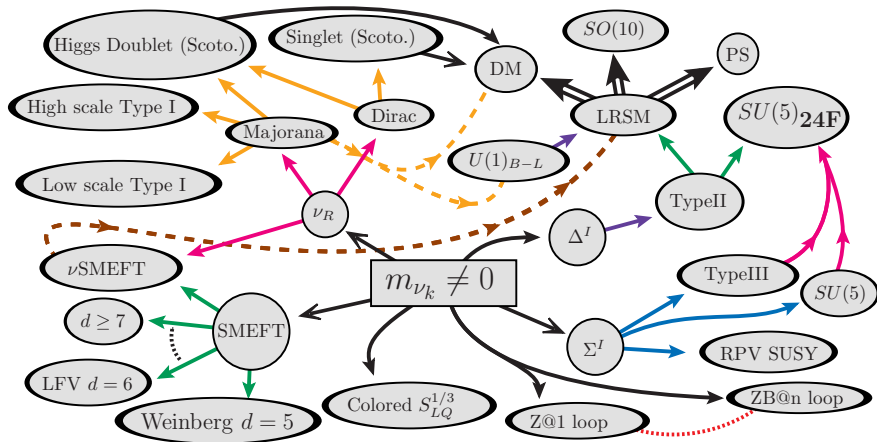
$m_\nu \neq 0 + \text{renormalizability} + \text{gauge inv.} \implies$ **new particles**

New particles must couple to Φ_{SM} and L , often inducing non-conservation of lepton symmetries

3. The Rich Person's Problem

Solution to $m_\nu \neq 0$ can be realized in *many* ways!

Minkowski ('77); Yanagida ('79); Glashow & Levy ('80); Gell-Mann et al., ('80); Mohapatra & Senjanović ('82); + *many* others



part 3: neutrino mass models at colliders

Overview of ν mass models

Many ways to categorize

Models with ν_R

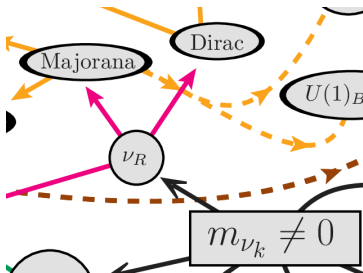
- Type I Seesaw (fermionic SU(2) singlet)
- $U(1)_{B-L}$ or Left-Right Symmetry (ν_R with new gauge charges)
- Type III Seesaw (fermionic SU(2) triplet)
- Scotogenic, KNT models

Models without ν_R

- Type II Seesaw (scalar SU(2) triplet)
- Zee-Babu (scalar SU(2) singlets but have hypercharge)

Important: new particles carry gauge charges and/or couple to Φ_{SM} and L

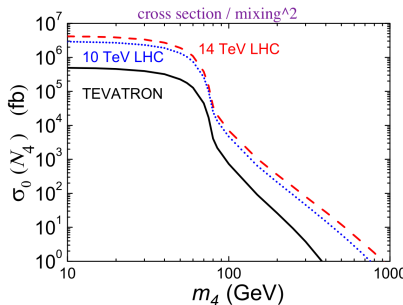
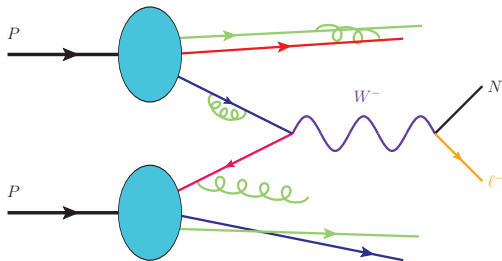
right-handed neutrinos¹



¹For reviews at colliders, see Cai, Han, Li, RR [[1711.02180](#)] and Pascoli, RR, Weiland [[1812.08750](#)]

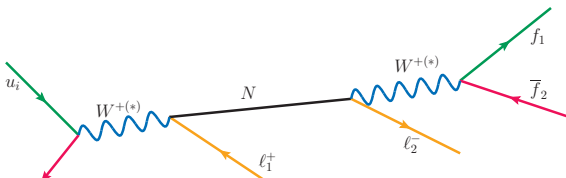
Historically, searches for N with $m_N \sim M_W$ relied on decays of $W^\pm$, or more generally $(q\bar{q})$ annihilation

Keung & Senjanovic (PRL'83)

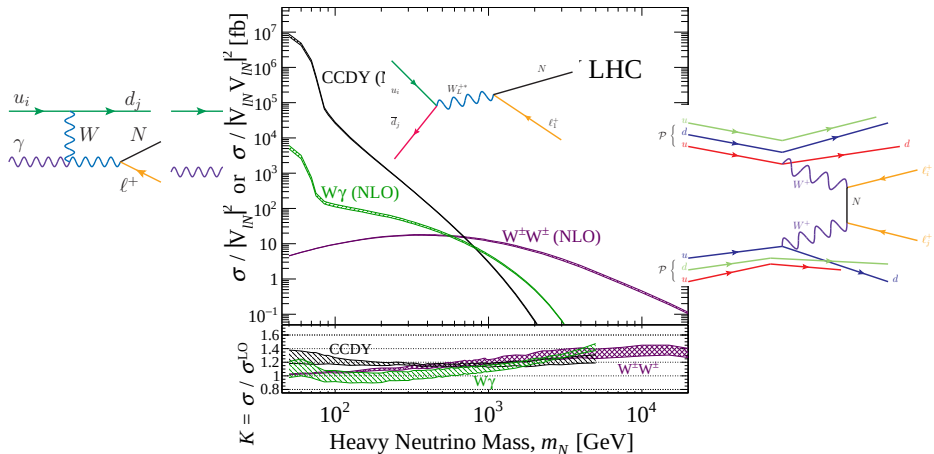


At **ATLAS** and **CMS**, search for $pp \rightarrow \ell_i \ell_j + \text{jets}$ or $\ell_i \ell_j \ell_k + \text{nothing}$

based on seminal works by K&S, del Aguila & Aguilar-Saavedra [0808.2468], and Atre, et al [0901.3589]



Plotted: Normalized production rate $(\sigma/|V|^2)^{(4)}$ vs m_N



$\gamma W^\pm$ and $W^\pm W^\pm$ scattering drive high-mass scattering rates!

Fuks, RR, et al [2011.02547; 2012.09882]

Physics ABOUT BROWSE PRESS COLLECTIONS

VIEWPOINT

Tracking Down the Origin of Neutrino Mass

Julia Schütte
Department of Theoretical Physics, CERN, Geneva, Switzerland
July 6, 2022 • Physics 26, 20

Collider experiments have set new direct limits on the existence of hypothetical heavy neutrinos, helping to constrain how ordinary neutrinos get their mass.



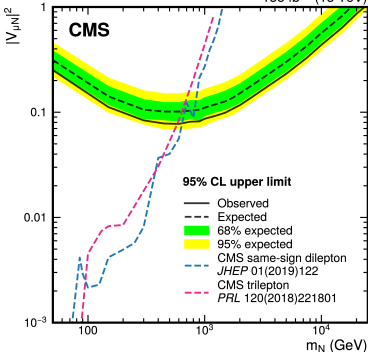
Recent Articles

Breakneck Outflows from Earth's Most Explosive Eruption
The 2022 eruption of a partially submerged volcano near Tonga produced spectra that hurried at 122 kilometers per hour—as determined by being the missing rupture of a smaller value.

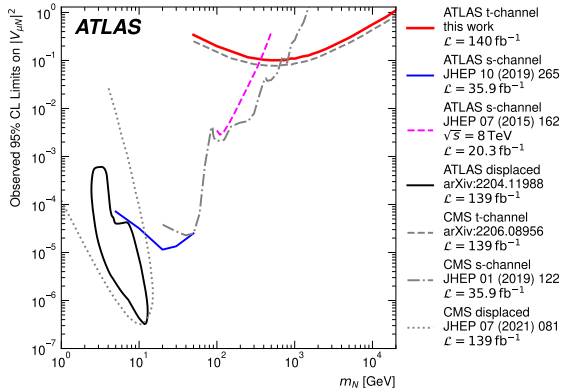
Striking a Balance for Quantum Bits
A demonstration that certain electron-transport processes can be tuned in a hybrid semiconductor-superconductor system could be useful for developing quantum computers.

Experiments Support Theory for Exotic Kagome States

138 fb⁻¹ (13 TeV)



Search for $W^\pm W^\pm \rightarrow \ell^\pm \ell'^\pm$ actively explored by **ATLAS** and **CMS** experiments!

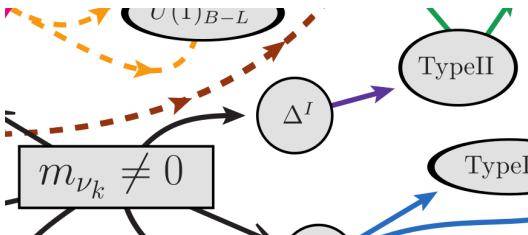


ATLAS (EPJC'23) [2305.14931]

$ee/e\mu$ (PLB'24) [2403.15016], $\tau\ell$ [2607.27307]

← CMS (PRL'22) [2206.08956]

Type II Seesaw²

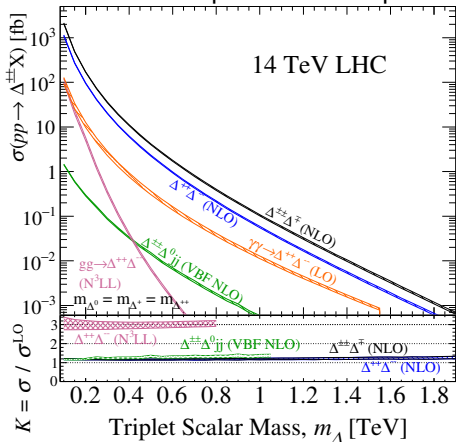


² Konetschny and Kummer ('77); Schechter and Valle ('80); Cheng and Li ('80); Lazarides, et al ('81); Mohapatra and Senjanovic ('81)

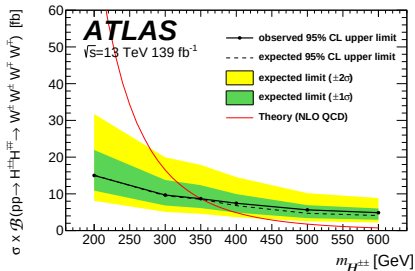
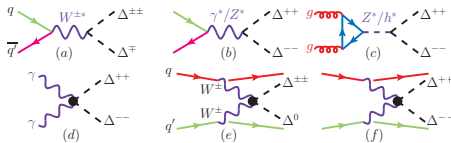
Type II Seesaw

Hypothesizes: new scalars $\Delta^{\pm\pm}, \Delta^{\pm}, \Delta^0, \xi^0$, all couple to W, Z, γ

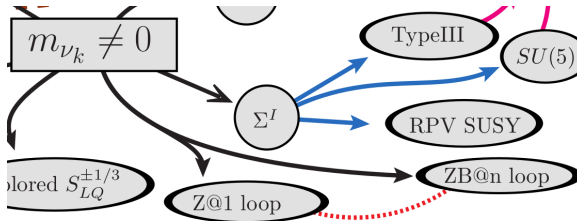
⇒ clear prediction for production rates; decay rates tied to PMNS!



Fuks, Nemevšek, RR [1912.08975]



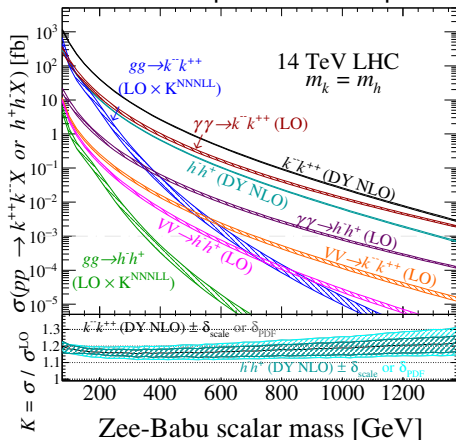
Zee-Babu Model³



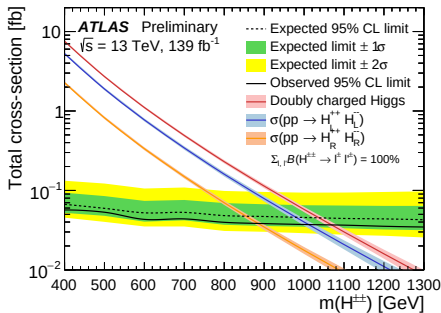
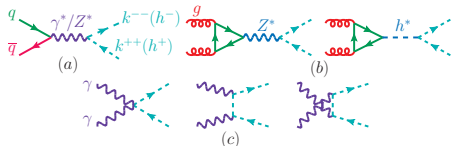
³Zee ('85×2), Babu ('88)

Hypothesizes: new scalars $h^{\pm\pm}$, $k^{\pm}$, both couple to W, Z, γ

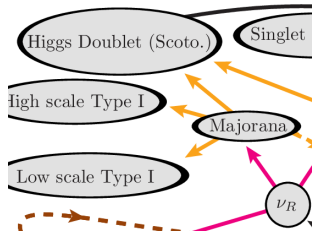
$\Rightarrow$ clear prediction for production rates; decay rates tied to PMNS!



RR [2206.14833]



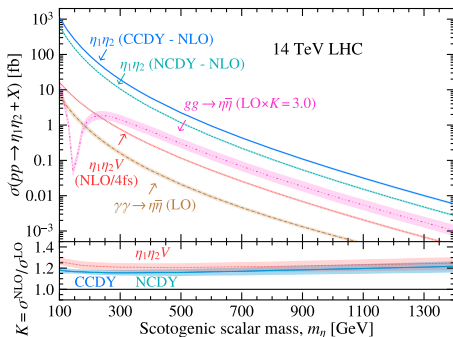
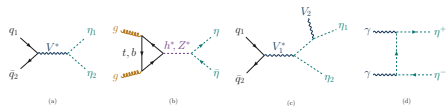
Scotogenic Model⁴



⁴ Tao ('96); Ma ('06)

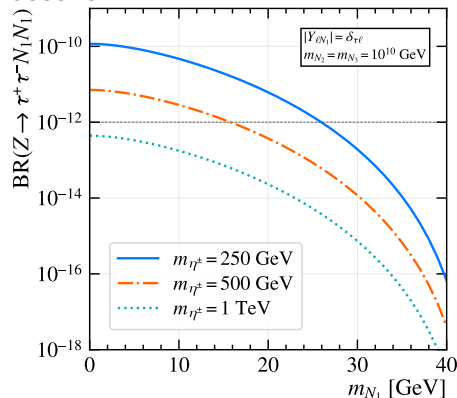
Scotogenic Model

Hypothesizes: new scalars $\eta^\pm, \eta_R^0, \eta_I^0$, all couple to W, Z, γ
 ν_R that couples to η and ℓ **Lightest particle dark matter!**

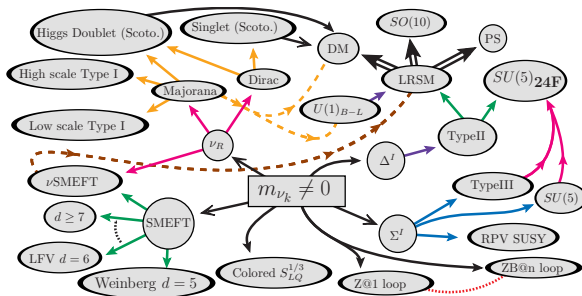


Boukidi, Ramos RR [2609.26876]

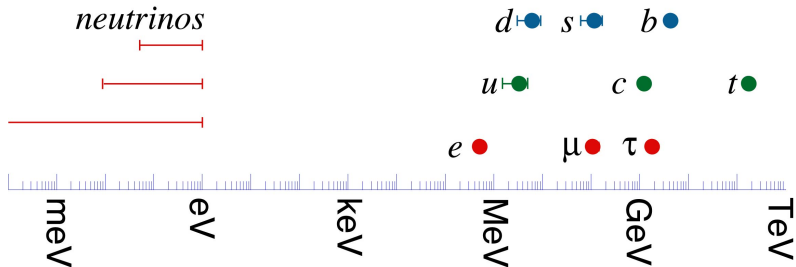
New rare decays of W and Z bosons



so much not covered



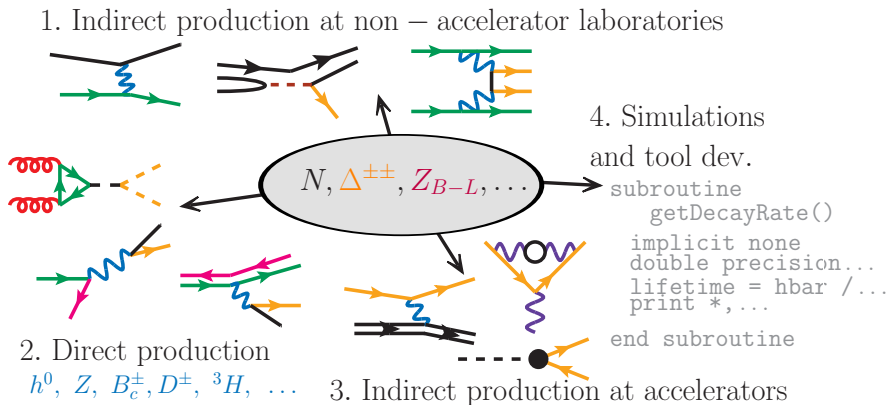
summary and conclusion



Unambiguous data that neutrino have nonzero masses

- contrary to the Standard Model (SM) of particle physics
- general arguments, more new particles must exist (unclear what kind)

broad implications for experimental physics



Many complementary ways to explore consequences of m_ν

- space! (underground-, ground-, water-, ice-based telescopes) ☺
- short and long baseline experiments and ν DIS facilities ☺
- direct production at colliders and ℓ -DIS facilities $\ell\ell, \ell h, hh$ ☺

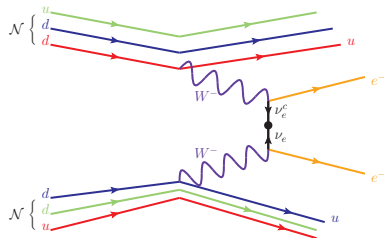
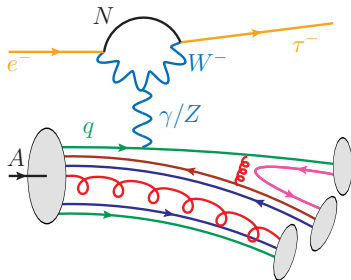


backup

friendly reminder of lepton symmetries

Lepton Number Violation (LNV) =
(#leptons - #antileptons) not conserved

e.g. nuclear $0\nu\beta\beta$ decay of heavy isotopes $(A, Z) \rightarrow (A, Z + 2) + e^- e^-$



Lepton Flavor Violation (LFV) =
(#lepton species - #antilepton species)
not conserved,

e.g. $e^- \rightarrow \tau^-$ conversion in deeply inelastic scattering (DIS)

lepton number and **lepton flavor** are **accidentally** conserved **in the SM**

The Black Box Theorem

LVN $\iff$ **Majorana nature of ν**

In '82, Schechter & Valle published (PRD'82) a seminal result:

- Suppose $0\nu\beta\beta$ is mediated within
“a 'natural' gauge theory” a $\Delta L = -2$ process

→

- u, d and e^- all carry weak charges

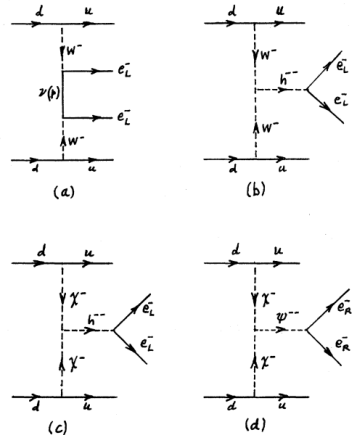


FIG. 1. Diagrams for neutrinoless double- β decay in an $SU(2) \times U(1)$ gauge theory. The standard diagram is Fig. 1(a). It is the only one which contains a virtual neutrino (of four-momentum p). d and u are the down and up quarks.

In '82, Schechter & Valle published (PRD'82) a seminal result:

- Suppose $0\nu\beta\beta$ is mediated within “a 'natural' gauge theory” a $\Delta L = -2$ process
→
- u, d and e^- all carry weak charges
- always possible to build a many-loop, 2-point graph with external ν_L, ν_L^c
- $0\nu\beta\beta$ generates a **Majorana mass** for ν
- holds generally for other $\Delta L \neq 0$ process
for further discussions, see:
Hirsch, et al [[hep-ph/0608207](https://arxiv.org/abs/hep-ph/0608207)] and Pascoli, et al [[1712.07611](https://arxiv.org/abs/1712.07611)]

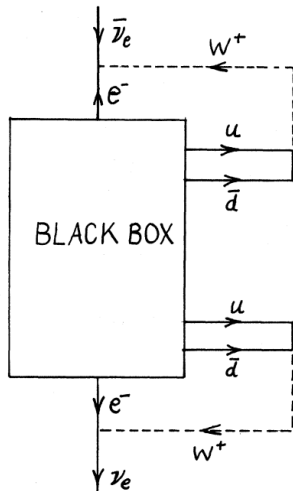


FIG. 2. Diagram showing how any neutrinoless double- β decay process induces a $\bar{\nu}_e$ -to- ν_e transition, that is, an effective Majorana mass term.