A Brief History of the Seesaw Mechanism

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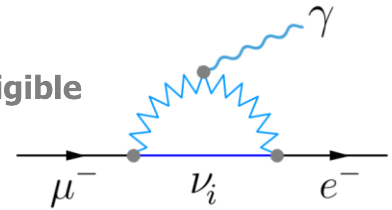
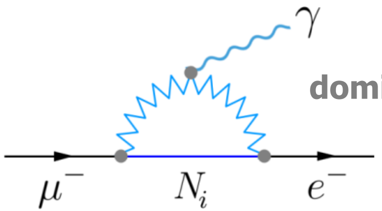
$\mu \to e + \gamma$ at a rate of one out of 10^9 muon decays?

P. Minowski, Phys. Lett. B 67 (1977) 421

negligible



light neutrinos



dominant

heavy neutrinos

Sino-Thai International Summer School on HEP&AP, 13~17.7.2026, Guangzhou

OUTLINE

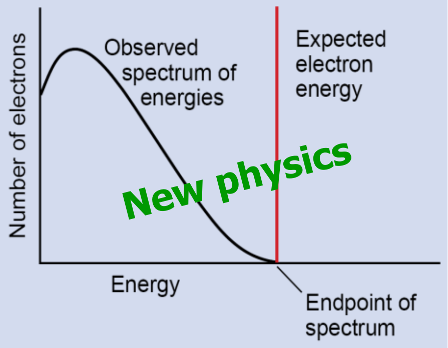
- Neutrinos: why massless in the SM?
- SMEFT $\rightarrow$ tiny and Majorana masses
- Minkowski mechanism: the likeliest
- Concluding remarks

Pauli's hypothesis: correct but self-misleading

♦ An unexpected continuous energy spectrum of outgoing electrons in a presumable two-body beta decay was observed (J. Chadwick 1914, C. Ellis 1920~1927), posing three theoretical challenges:

- Energy conservation violated?
- Lepton number conservation violated?
- Spin angular momentum conservation violated! (½ ≠ ½ ⊕ ½ = 1, 0)

$$n \to p + e^-$$



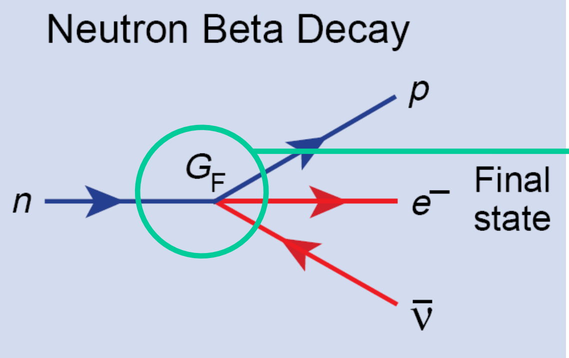
♦ It was W. Pauli, father of the Pauli exclusion principle (1925), who killed the three birds with one stone —— a light, neutral and spin-half particle (1930), the electron antineutrino: $n \to p + e^- + \overline{\nu}_e$

♦ But the discovery of that hypothetical particle was too late (1956), making Pauli miss a chance to become the father of non-Abelian gauge symmetry in 1953. It is said that Pauli said:

> I have already introduced one hypothetical massless particle, and I had no nerve to introduce more —— *Standing Together in Troubled Times* (edited by M. Shifman, World Scientific, 2017)

From Fermi's EFT to Weinberg's SM

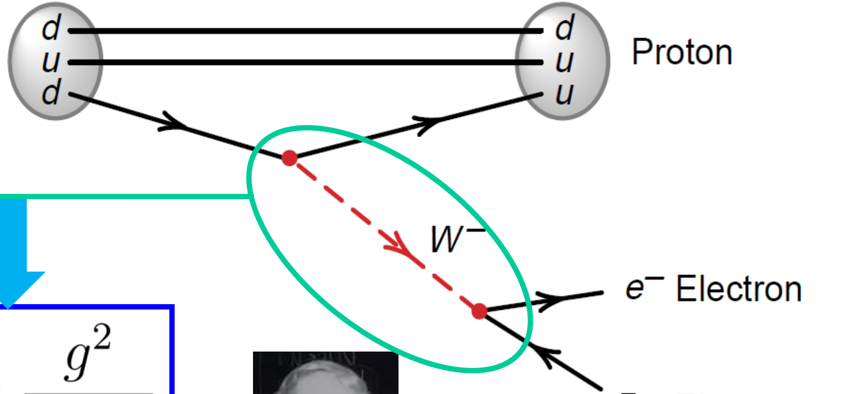
♦ **E. Fermi established the β-decay EFT (1933/1934), a great step towards S. Weinberg's SM (1967)**



$$G_F(\overline{\psi}_p\,\gamma_\mu\,\psi_n)(\overline{\psi}_e\,\gamma^\mu\gamma_5\,\psi_\nu)$$

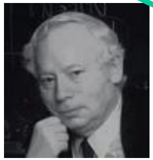
V **A**

Dimension-6: ***non-renormalizable***



$$\boxed{\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2}}$$

gauge seesaw



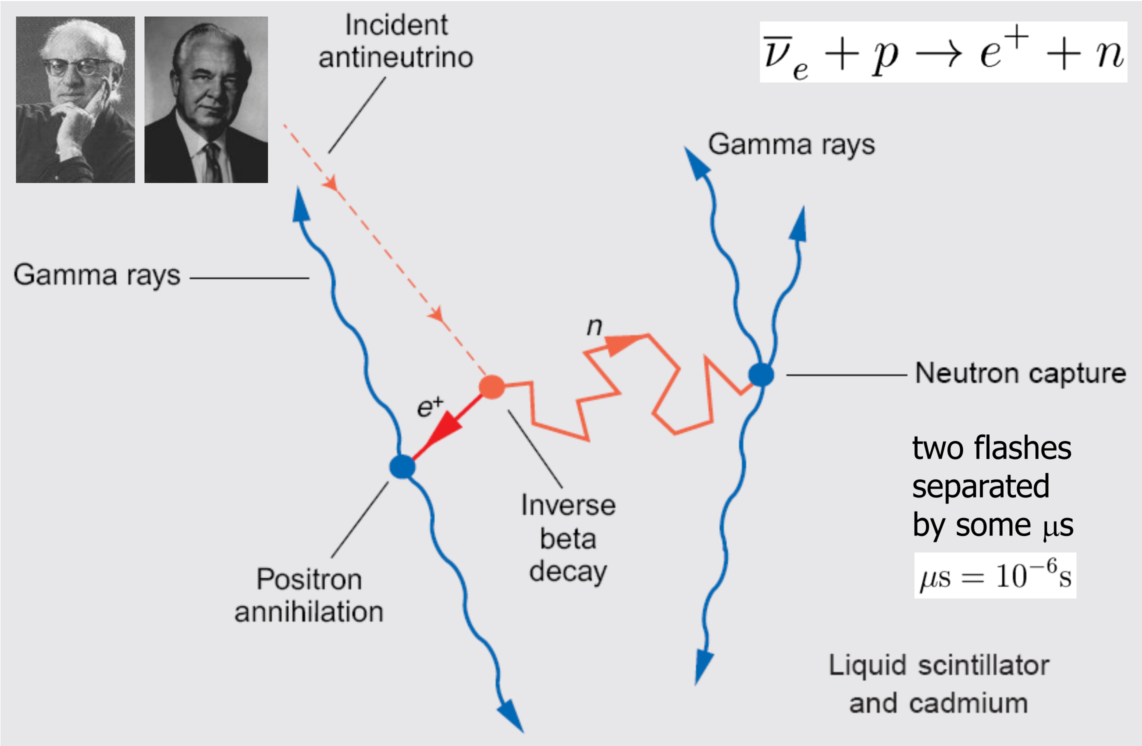
Dimension-4: ***renormalizable***

Fermi coupling constant	**Weak interaction coupling constant**
$G_F \simeq 1.166 \times 10^{-5}\ \mathrm{GeV}^{-2}$	$g \simeq 0.65$ **vs** $M_W \simeq 80.4\ \mathrm{GeV}$

A good lesson: **some effective quantities at low energies are very likely to originate from new heavy degrees of freedom in a more fundamental theory at much higher energy scales.**

Fermi's best theory worked well

♦ **F. Reines and C. Cowan discovered reactor antineutrinos (1956). But it's already too late for Pauli.**



B. Pontecorvo 1946

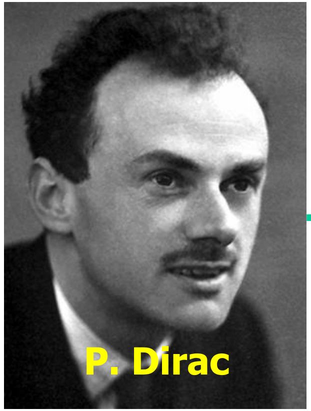
- **Parity violation: TH (1956) by T.D. Lee, C.N. Yang**
- **Parity violation: EX (1957) by C.S. Wu / L. Lederman et al**
- **V–A theory of weak force (1958) by R. Feynman, M. Gell-Mann; ...**
- **Neutrino's negative helicity (1958) by M. Goldhaber et al**

- **All neutrinos were measured in US**

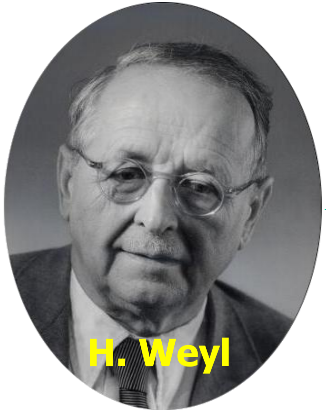
♦ **A consensus on neutrinos for most physicists at that time: massless & left-handed Weyl fermions.**

That's a reasonable expectation

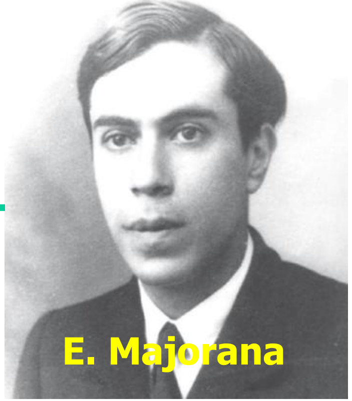
- **T.D. Lee** and **C.N. Yang, L. Landau**, and **A. Salam** all conjectured neutrinos to be **massless** in **1957**.



$m = 0$



$m = 0$



1928 **1929** **1937**

- **But B. Pontecorvo, a key member of the Fermi school, believed that neutrinos should be massive.**

"Mesonium and Anti-mesonium" in Sov. Phys. JETP 6 (1957) 429.

If the two-component neutrino theory turned out to be incorrect and if the conservation law of neutrino charge didn't apply, then neutrino—antineutrino transitions would in principle be possible to take place in vacuum.

Weinberg's razor

VOLUME 19, NUMBER 21 PHYSICAL REVIEW LETTERS 20 NOVEMBER 1967

Citations > 15000

A MODEL OF LEPTONS*

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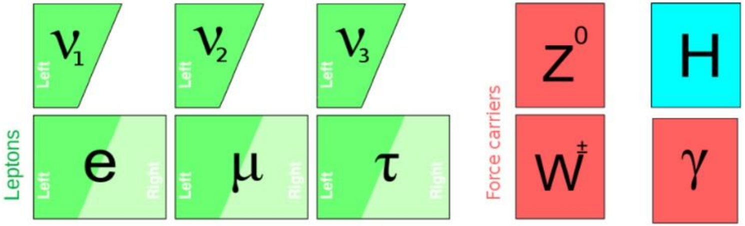
(Received 17 October 1967)



- ♦ It is a *renormalizable* $SU(2)_L \times U(1)_Y$ gauge theory.
- ♦ Its particle content is so *economical* that there is no way to make neutrinos massive.

- ♦ A Dirac neutrino mass term impossible.
- ♦ A Majorana neutrino mass term impossible.
- ♦ An effective (non-renormalizable) neutrino mass term impossible.

The 1st hint for ν-mass emerged soon

♦ Just about six months later, R. Davis reported *the first experimental hint* for a solar B-8 neutrino deficit as compared with the prediction of the standard solar model → solar neutrino oscillations.

VOLUME 20, NUMBER 21 PHYSICAL REVIEW LETTERS 20 MAY 1968

SEARCH FOR NEUTRINOS FROM THE SUN*

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(Received 16 April 1968)

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NEUTRINO ASTRONOMY AND LEPTON CHARGE

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Received 20 December 1968

It is shown that lepton nonconservation might lead to a decrease in the number of detectable solar neutrinos at the earth surface, because of $\nu_e \rightleftarrows \nu_\mu$ oscillations, similar to $K^0 \rightleftarrows \tilde{K}^0$ oscillations. Equations are presented describing such oscillations for the case when there exist only four neutrino states.

OUTLINE

- Neutrinos: why massless in the SM?
- SMEFT $\rightarrow$ tiny and Majorana masses
- Minkowski mechanism: the likeliest
- Concluding remarks

From SM to SMEFT

♦ It was S. Weinberg who invented the *SMEFT* in 1979, as a low-energy effective way to go beyond the SM, in particular to generate tiny Majorana neutrino masses.

The standard electroweak theory

$$\boxed{\mathcal{L}_{\rm SM} = \mathcal{L}_{\rm gauge} + \mathcal{L}_{\rm Higgs} + \mathcal{L}_{\rm fermion} + \mathcal{L}_{\rm Yukawa}}$$

(in which neutrinos are massless)

$$\mathcal{L}_{\rm G} = -\frac{1}{4}\left(W^{i\mu\nu}W^{i}_{\mu\nu} + B^{\mu\nu}B_{\mu\nu}\right)$$

$$\mathcal{L}_{\rm H} = (D^{\mu}H)^{\dagger}(D_{\mu}H) - \mu^2 H^{\dagger}H - \lambda(H^{\dagger}H)^2$$

$$\mathcal{L}_{\rm F} = \overline{Q_{\rm L}}\,{\rm i}\not{D}\,Q_{\rm L} + \overline{\ell_{\rm L}}\,{\rm i}\not{D}\,\ell_{\rm L} + \overline{U_{\rm R}}\,{\rm i}\not{\partial}'\,U_{\rm R} + \overline{D_{\rm R}}\,{\rm i}\not{\partial}'\,D_{\rm R} + \overline{E_{\rm R}}\,{\rm i}\not{\partial}'\,E_{\rm R}$$

$$\mathcal{L}_{\rm Y} = -\overline{Q_{\rm L}}\,Y_{\rm u}\widetilde{H}U_{\rm R} - \overline{Q_{\rm L}}\,Y_{\rm d}HD_{\rm R} - \overline{\ell_{\rm L}}\,Y_{l}HE_{\rm R} + {\rm h.c.}$$

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_{\forall i, n\geq 5} \frac{C_i \mathcal{O}_i^{(n)}}{\Lambda^{n-4}}$$

Higher (mass) dimension operators suppressed by NP scale

I must say that I am not a model builder!

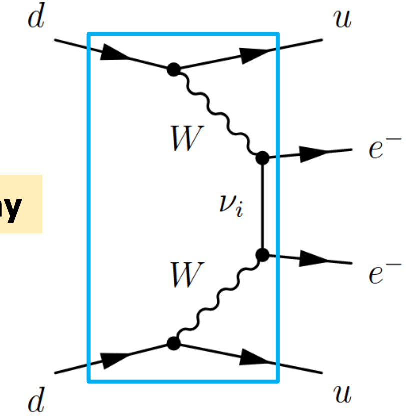
♦ Weinberg: My style is usually not to propose specific models that will lead to specific experimental predictions, but rather to interpret *in a broad way* what is going on and make very general remarks, like with the development of the viewpoint associated with effective field theory. (CERN Courier 2021)

A model-independent way

♦ Do you believe in the SM? Do you believe in the SMEFT? Do you trust their natural consequences?

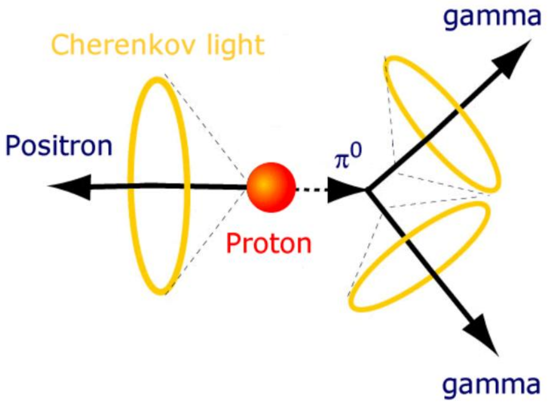
$$\text{SMEFT} = \text{SM}\ (d=4) + \underbrace{\boxed{\frac{HHLL}{\Lambda}}}_{d=5} + \underbrace{\boxed{\frac{QQQL}{\Lambda^2}}}_{d=6} + \cdots$$

- **Yukawa** interactions of neutrinos
- tiny ν-masses $\to$ flavor oscillation
- $\Delta\,(\mathrm{B}-\mathrm{L}) = 2 \to$ **Majorana** nature



0ν2β decay

- $\Delta\,(\mathrm{B}-\mathrm{L}) = 0 \to$ proton decay



♦ **Discussion**: If you see the proton decay which is surely L-violating, will neutrinos be of Majorana?

The unique Weinberg operator

♦ **The SMEFT approach leads us to the first and unique non-renormalizable dimension-five operator, written out by S. Weinberg in 1979:**

"unique" d=5 operator

$$\boxed{\frac{1}{2} C_{\alpha\beta} \frac{\overline{\ell_{\alpha \mathrm{L}}} \widetilde{H} \widetilde{H}^T \ell^c_{\beta \mathrm{L}}}{\Lambda}}$$

- **Yukawa interactions**
- **tiny neutrino masses**
- **the Majorana nature**

(B—L) violation

spontaneous symmetry breaking

$$\boxed{-\mathcal{L}_{\rm mass} = \frac{1}{2} \overline{\nu_{\rm L}} M_\nu \nu^c_{\rm L} + {\rm h.c.}}$$

$$\boxed{\frac{G_{\rm F}}{\sqrt{2}} = \frac{g^2}{8 M_W^2}}$$

seesaw-like

Naturally tiny: $\mathcal{O}(0.1)\ \ {\rm eV}$ $\boxed{(M_\nu)_{\alpha\beta} = C_{\alpha\beta} \frac{\langle H \rangle^2}{\Lambda}}$

$$C_{\alpha\beta} \sim \mathcal{O}(1),\ \langle H \rangle \sim 10^2\ \ {\rm GeV}$$

$$\Lambda \sim 10^{14}\ \ {\rm GeV}$$

Is the PMNS matrix really unitary?

♦ There exist **d=6** operators relevant to lepton flavor mixing in the *SMEFT*, leading to non-unitarity of the **PMNS** matrix ***U*** (A. Broncano, B. Gavela, E. Jenkins 2003; D. Zhang, S. Zhou 2021; ...).

$$\mathcal{L}_{\nu\rm SM} = \mathcal{L}_{\rm SM} + \left[\frac{1}{2} C^{(5)}_{\alpha\beta} \frac{\mathcal{O}^{(5)}_{\alpha\beta}}{\Lambda} + {\rm h.c.}\right] + \underline{C^{(6)}_{\alpha\beta} \frac{\mathcal{O}^{(6)}_{\alpha\beta}}{\Lambda^2}} + \cdots$$

At the **tree** level, the two types of operators are of the following forms:

$$\mathcal{O}^{(5)}_{\alpha\beta} = \left(\overline{\ell_{\alpha \rm L}}\, \widetilde{H}\right)\left(\widetilde{H}^T \ell^c_{\beta \rm L}\right)$$

The ν-mass operator: (B–L) violating

$$\mathcal{O}^{(6)}_{\alpha\beta} = \left(\overline{\ell_{\alpha \rm L}}\, \widetilde{H}\right) {\rm i}\gamma_\mu \partial^\mu \left(\widetilde{H}^\dagger \ell_{\beta \rm L}\right)$$

PMNS non-unitarity: (B–L) conserving

♦ Remark (1): both operators arise from the Yukawa interactions between the Higgs and neutrinos.

♦ Remark (2): Non-unitarity of the PMNS matrix may be tiny, but cannot be exactly zero.

♦ Remark (3): Yukawa couplings and Majorana nature of massive neutrinos are two key clues to go beyond the SM, as clearly indicated by the SMEFT. How to go in a renormalizable way?

OUTLINE

- Neutrinos: why massless in the SM?
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A footnote as the seed of seesaw

In collaboration with Fritzsch and Gell-Mann, Minkowski proposed the first seesaw idea to interpret tiny neutrino masses in a footnote of their paper in 1975.

Volume 59B, number 3 PHYSICS LETTERS 10 November 1975

VECTORLIKE WEAK CURRENTS AND NEW ELEMENTARY FERMIONS *

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Received 15 September 1975

Recent experimental discoveries encourage speculation that there may be more than four "flavors" of tricolored quarks and/or new flavors of leptons. A vectorlike gauge theory of the weak, electromagnetic, and associated neutral current interactions is then an attractive possibility. We present as an illustrative example a minimal theory based on six quark flavors and six lepton flavors and on the group $SU_2 \times U_1$ (presumably a subgroup of a larger gauge group).

- After inventing the SO(10) GUT, Harald and Peter paid much attention to heavy fermions, as well as neutrino oscillations. They tried to address some important issues beyond Weinberg's model.
- Was Gell-Mann himself interested in the seesaw idea? He, P. Ramond and R. Slansky had a highly cited conference paper "Complex spinors and unified theories" in 1979. They quoted no references!

This footnote is very valuable, but it is not that famous. To my best knowledge, the best known footnote is the one in M. Gell-Mann and M. Levy's paper published in 1960, a seminal work for lepton and quark flavor mixing.

We consider here the most economical theory of the type we have discussed that is not in direct disagreement with observation, namely, one with six flavors of quark and six flavors of lepton. The SU_2^{weak} doublets are as follows, ignoring angles that must be relatively small:

$$\text{quarks:}\quad \left(\begin{array}{cc|c} u & t & c \\ d' & b & s' \end{array}\right)_L \quad \left(\begin{array}{cc|c} t & u & c \\ d'' & b & s'' \end{array}\right)_R ,$$

$$\text{leptons:}\quad \left(\begin{array}{cc|c} \nu_e & N_M & \nu_\mu \\ e^- & M^- & \mu^- \end{array}\right)_L \quad \left(\begin{array}{cc|c} N_M & \nu_e & N_\mu \\ e^- & M^- & \mu^- \end{array}\right)_R .$$

We assume that the neutral lepton N_M is a Dirac particle, with a mass term that conserves lepton number[‡3]. Violation of lepton number is assumed to occur only through the mass term of the Majorana spinor N_μ, composed of the right-handed muon neutrino and its antiparticle. The remaining two component spinors $(\nu_e)_L$, $(\nu_e)_R$ and $(\nu_\mu)_L$ are assumed to be massless in the absence of interactions[‡4].

‡4 In the present state of symmetry-breaking theory, we do not understand how, in the absence of cumbersome machinery, to calculate finite mass corrections arising from weak and electromagnetic interactions. Nevertheless, we can attempt to estimate such effects by cutting off logarithmic infinities at a mass Λ of order M_X. Let us do so, for example, in case of the muon neutrino. The off-diagonal element of the mass matrix between ν_μ and N_μ is of order $\alpha\pi^{-1} m_\mu \ln(\Lambda^2 m_X^{-2})$ and the muon neutrino acquires a mass (besides the intrinsic fourth order term) of order $m_\mu^2 m_{N}^{-1}[\alpha\pi^{-1}\ln(\Lambda^2 m_X^{-2})]^2$, which might be around 20 eV for $m_{N_\mu} \sim 2$ GeV. The electron neutrino acquires a tiny mass $\ll 1$ eV through mixing with N_M. These masses are

m_D

Seesaw:

$$\boxed{m_\nu = \frac{m_D^2}{m_N}}$$

In 1977 this idea was developed into a complete seesaw mechanism by Peter. His paper was not well recognized until 2004, after the so-called seesaw'25 event, counted by the organizers from 1979 on.

The complete Swiss-made seesaw

In 1977, Harald mainly worked at CERN and Wuppertal Univ, while Peter joined Univ of Bern. Peter published a big paper soon after becoming a faculty member.

Volume 67B, number 4 PHYSICS LETTERS 25 April 1977

$\mu \to e\gamma$ AT A RATE OF ONE OUT OF 10^9 MUON DECAYS?

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The framework is much sounder.

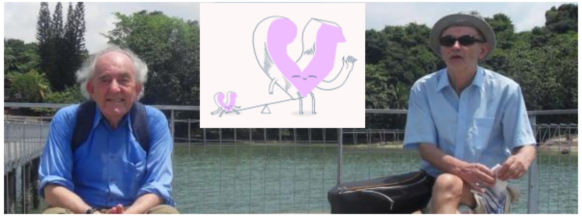
Received 28 February 1977

The spirit is basically the same.

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L, \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L; \quad \begin{pmatrix} N_e \\ e^- \end{pmatrix}_R, \quad \begin{pmatrix} N_\mu \\ \mu^- \end{pmatrix}_R. \qquad \mu = \begin{pmatrix} 0 & \mathcal{M}_n \\ \mathcal{M}_n^T & N_R \end{pmatrix} \qquad m_\nu = O\left(\frac{|\mathcal{M}_n|^2}{m^N_{1,2}}\right) \lesssim 10 \text{ eV}$$

A unitary matrix + a block diagonalization: seesaw relation.

$$\upsilon = \begin{pmatrix} \upsilon_{11} & \upsilon_{12} \\ \upsilon_{21} & \upsilon_{22} \end{pmatrix}: \qquad \upsilon_{11} \begin{pmatrix} m_1^\nu & 0 \\ 0 & m_2^\nu \end{pmatrix} \upsilon_{11}^T \approx -\mathcal{M}_n N_R^{-1} \mathcal{M}_n^T$$

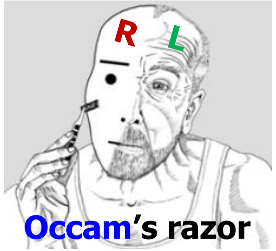


Why this mechanism is most natural?

- Neutrinos surely have the *right* to be *right* (-handed) to keep an analogous *left-right symmetry* as charged leptons or quarks.

$$\begin{pmatrix} u_{\rm L} \\ d_{\rm L} \end{pmatrix} \begin{matrix} \Longleftrightarrow \\ \Longleftrightarrow \end{matrix} \begin{matrix} u_{\rm R} \\ d_{\rm R} \end{matrix}$$

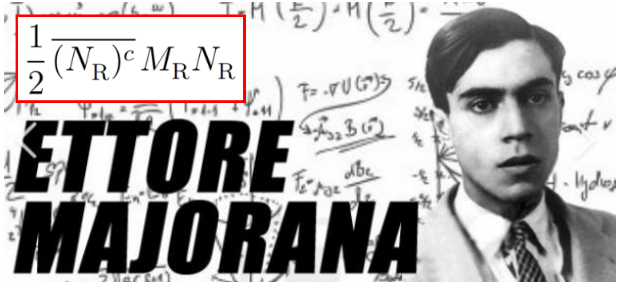
$$\begin{pmatrix} \nu_{e\rm L} \\ e_{\rm L} \end{pmatrix} \begin{matrix} \Longleftrightarrow \\ \Longleftrightarrow \end{matrix} \begin{matrix} ? \\ e_{\rm R} \end{matrix}$$



Please note that right-handed fields are NoT the mirror counterparts of left-handed ones.

- Then neutrinos are allowed to couple to the SM Higgs doublet —— the Yukawa interactions. Why not?

- But the gender of neutrinos (neutral) makes it very fair to add a Majorana mass term with N and N^c, which is fully *harmless* to all the fundamental symmetries of the SM.



- Then we are led to the Minkowski mechanism, which works even before SSB of the SM:

$$\mathcal{L}_{\nu\rm SM} = \mathcal{L}_{\rm SM} + \overline{N_{\rm R}}\, {\rm i}\gamma_\mu \partial^\mu N_{\rm R} - \left[\overline{\ell_{\rm L}}\, Y_\nu \widetilde{H} N_{\rm R} + \underline{\frac{1}{2}\overline{(N_{\rm R})^c} M_{\rm R} N_{\rm R}} + {\rm h.c.}\right]$$

(B—L) violation

$$= \mathcal{L}_{\rm SM} + \overline{N_{\rm R}}\, {\rm i}\gamma_\mu \partial^\mu N_{\rm R} - \left[\frac{1}{2}\overline{\left[\nu_{\rm L} \;\; (N_{\rm R})^c\right]} \begin{pmatrix} \mathbf{0} & Y_\nu \underline{\phi^{0*}} \\ Y_\nu^T \underline{\phi^{0*}} & M_{\rm R} \end{pmatrix} \begin{bmatrix} (\nu_{\rm L})^c \\ N_{\rm R} \end{bmatrix} - \overline{l_{\rm L}}\, Y_\nu N_{\rm R} \underline{\phi^-} + {\rm h.c.}\right]$$

The exact seesaw formula

♦ A basis transformation to obtain **Majorana** neutrino masses and flavor mixing before or after **SSB**.

$$\mathbb{U}^\dagger \begin{pmatrix} \mathbf{0} & Y_\nu \phi^{0*} \\ Y_\nu^T \phi^{0*} & M_{\rm R} \end{pmatrix} \mathbb{U}^* = \begin{pmatrix} D_\nu & \mathbf{0} \\ \mathbf{0} & D_N \end{pmatrix}$$

The three-block decomposition: **ZZX**, **1110.0083**

$$\mathbb{U} = \underbrace{\begin{pmatrix} I & \mathbf{0} \\ \mathbf{0} & U_0' \end{pmatrix}}_{\text{sterile (unitary)}} \underbrace{\begin{pmatrix} A & R \\ S & B \end{pmatrix}}_{\text{Yukawa (interplay)}} \underbrace{\begin{pmatrix} U_0 & \mathbf{0} \\ \mathbf{0} & I \end{pmatrix}}_{\text{active (unitary)}}$$

$$\left(O_{56} O_{46} O_{45}\right) \left[O_{36} O_{26} O_{16} O_{35} O_{25} O_{15} O_{34} O_{24} O_{14}\right] \left(O_{23} O_{13} O_{12}\right)$$

working masses:

$$\begin{cases} D_\nu \equiv {\rm Diag}\{m_1, m_2, m_3\} \\ D_N \equiv {\rm Diag}\{M_4, M_5, M_6\} \end{cases}$$

♦ **Weak charged-current interactions of leptons in the seesaw mechanism:**

$$-\mathcal{L}_{\rm cc} = \frac{g}{\sqrt{2}} \overline{\begin{pmatrix} e & \mu & \tau \end{pmatrix}_{\rm L}} \gamma^\mu \left[\underset{\text{light}}{U} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}_{\rm L} + \underset{\text{heavy}}{R} \begin{pmatrix} N_4 \\ N_5 \\ N_6 \end{pmatrix}_{\rm L} \right] W_\mu^- + {\rm h.c.}$$

oscillations, LNV, LFV ⟵ light **heavy ⟶ collider, cosmology**

$U = AU_0$: **the PMNS matrix**

R : **an analogue for heavy**

$$U D_\nu U^T = ({\rm i}R)\, D_N\, ({\rm i}R)^T$$

$$\underline{UU^\dagger + RR^\dagger = I}$$ **(unitarity relation)**

- **The PMNS matrix U is not exactly unitary in the seesaw scenario.**
- **But non-unitarity of U is constrained to be very small.**

From seesaw to SMEFT

♦ **Integrating out the heavy degrees of freedom —— right-handed neutrino fields, one may arrive at the seesaw EFT matching with the SMEFT (see A. Broncano, M.B. Gavela, E. Jenkins 2003; A. Abada, C. Biggio, F. Bonnet, M.B. Gavela, T. Hambye 2007; D. Zhang, S. Zhou 2021; ...).**

$$\mathcal{L}_{\nu\mathrm{SM}} = \mathcal{L}_{\mathrm{SM}} + \left[\frac{1}{2} C^{(5)}_{\alpha\beta} \frac{\mathcal{O}^{(5)}_{\alpha\beta}}{\Lambda} + \mathrm{h.c.}\right] + C^{(6)}_{\alpha\beta} \frac{\mathcal{O}^{(6)}_{\alpha\beta}}{\Lambda^2} + \cdots$$

At the tree level, one obtains

$$\mathcal{O}^{(5)}_{\alpha\beta} = \left(\overline{\ell_{\alpha\mathrm{L}}}\, \widetilde{H}\right)\left(\widetilde{H}^T \ell^c_{\beta\mathrm{L}}\right)$$

The Weinberg operator: (B–L) violating

$$\mathcal{O}^{(6)}_{\alpha\beta} = \left(\overline{\ell_{\alpha\mathrm{L}}}\, \widetilde{H}\right) \mathrm{i}\gamma_\mu \partial^\mu \left(\widetilde{H}^\dagger \ell_{\beta\mathrm{L}}\right)$$

The PMNS non-unitarity: (B–L) conserving

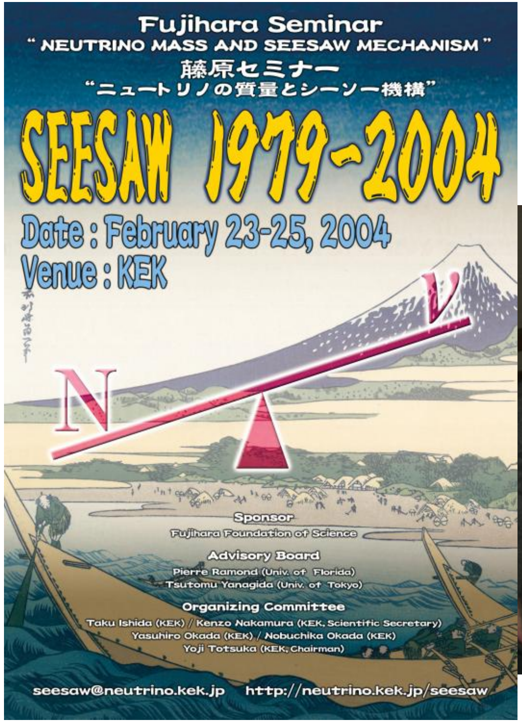
$$\frac{C^{(5)}_{\alpha\beta}}{\Lambda} = \left(Y_\nu M_{\mathrm{R}}^{-1} Y_\nu^T\right)_{\alpha\beta}$$

$$\frac{C^{(6)}_{\alpha\beta}}{\Lambda^2} = \left(Y_\nu |M_{\mathrm{R}}|^{-2} Y_\nu^\dagger\right)_{\alpha\beta}$$

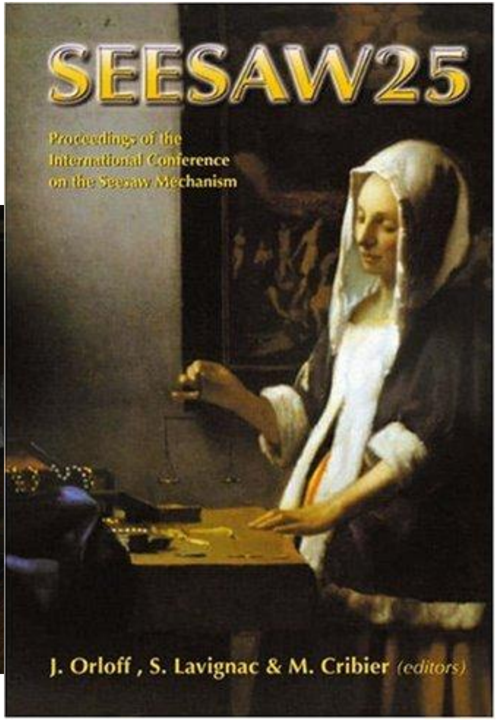
$$U = \left[I - \frac{1}{2}\langle H\rangle^2 \left(Y_\nu |M_{\mathrm{R}}|^{-2} Y_\nu^\dagger\right)\right] U_0^{(5)} = \left[I - \frac{1}{2} R R^\dagger\right] U_0^{(5)}$$

Who tried to claim credit for seesaw?

It was Paul Frampton who called attention to Peter's paper during the seesaw'25 on 10~11.6.2004 in Paris. A similar workshop, entitled Seesaw 1979~2004, was held on 23~25.2.2004 in Tsukuba. It was Pierre Ramond and Tsutomu Yanagida who claimed credit for seesaw in these two events.



Hi, old chaps,
what are you doing?

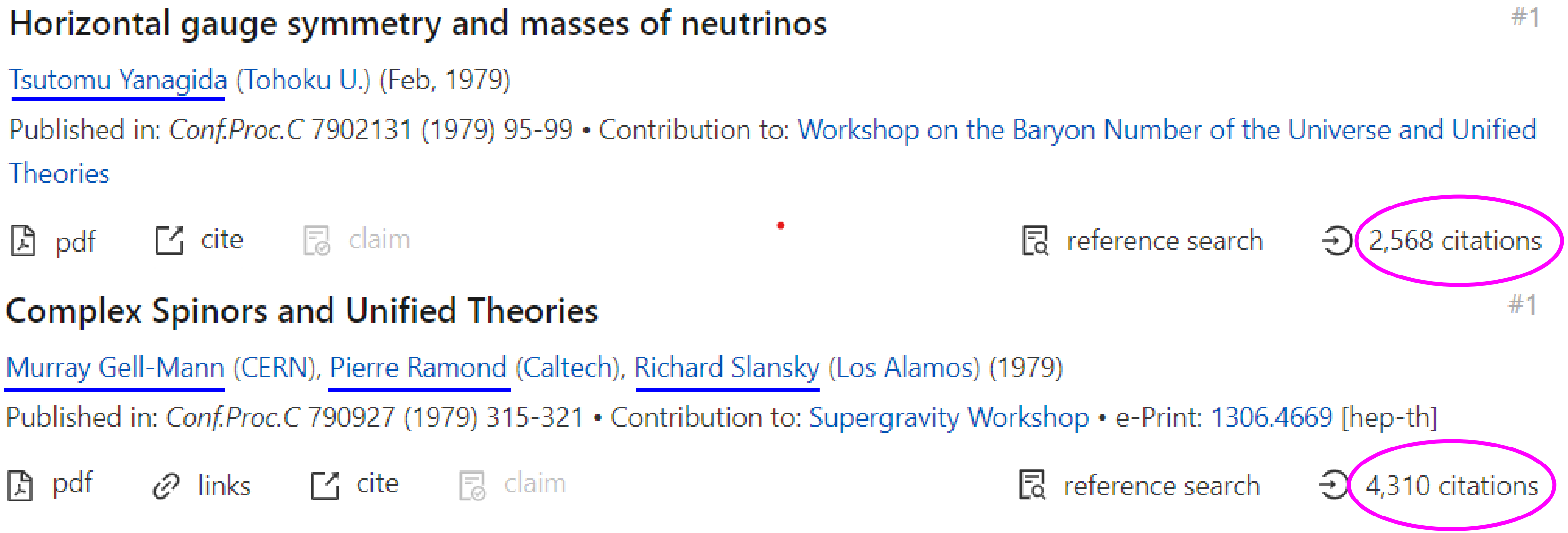


Paul once asked me why Harald did not claim credit for seesaw? Harald said he didn't care about it.

The citations didn't lie

Before and after June 2004, namely, 27 years to 22 years (up to today), the citations of Peter's that paper have really taught us something —— life is sometimes unpredictable.

$$\frac{\sim 20}{\sim 5890}$$


Horizontal gauge symmetry and masses of neutrinos #1
Tsutomu Yanagida (Tohoku U.) (Feb, 1979)
Published in: *Conf.Proc.C* 7902131 (1979) 95-99 • Contribution to: Workshop on the Baryon Number of the Universe and Unified Theories
pdf cite claim reference search 2,568 citations
Complex Spinors and Unified Theories #1
Murray Gell-Mann (CERN), Pierre Ramond (Caltech), Richard Slansky (Los Alamos) (1979)
Published in: *Conf.Proc.C* 790927 (1979) 315-321 • Contribution to: Supergravity Workshop • e-Print: 1306.4669 [hep-th]
pdf links cite claim reference search 4,310 citations

Paul did a good thing for the community

Why not just a Dirac mass?

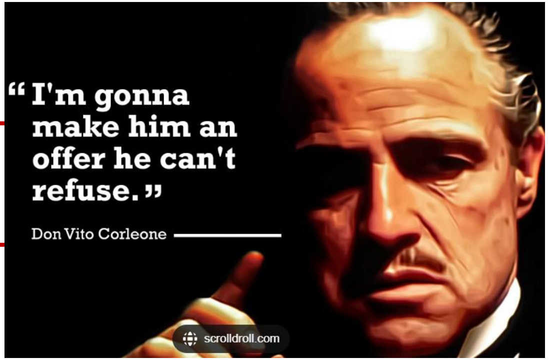
♦ It is cheap to write out a Dirac neutrino mass term, but it is expensive to abandon the associated Majorana mass term —— a buy-one-get-one-free sale, but the "free" one is not really free!

If you like a Dirac mass term: $\overline{\nu_{\alpha \rm L}} (M_{\rm D})_{\alpha\beta} \nu_{\beta \rm R}$ No one criticizes your choice.

If you abandon the Majorana term: $\overline{(\nu_{\alpha \rm R})^c} (M_{\rm R})_{\alpha\beta} \nu_{\beta \rm R}$ Pls make me an offer I can't refuse.

M. Gell-Mann's totalitarian principle (1956)

Everything not forbidden is compulsory!



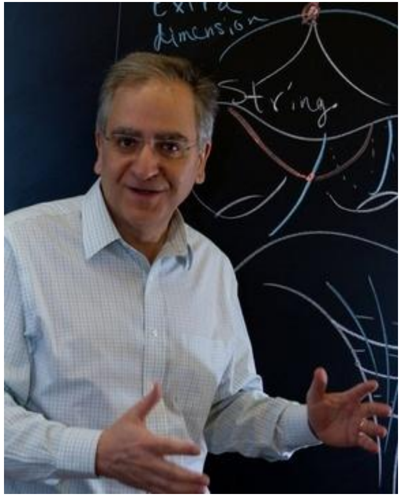
♦ a Dirac neutrino mass model can not naturally be built, unless lepton number symmetry is ad hoc imposed on it with the help of some new physics beyond the SM (R. Volkas, 2409.09992).

OUTLINE

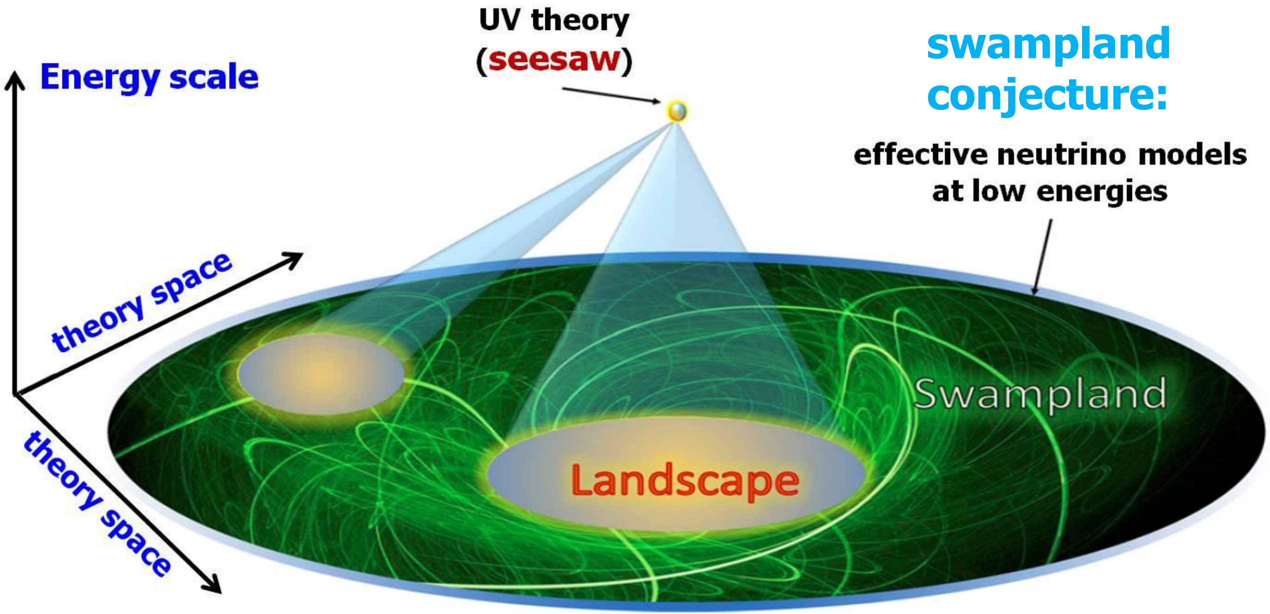
- ♦ **Neutrinos: why massless in the SM?**
- ♦ **SMEFT $\rightarrow$ tiny and Majorana masses**
- ♦ **Minkowski mechanism: the likeliest**
- ♦ **Concluding remarks**

Seesaw is in the Landscape, but...

♦ **Following the naturalness and simplicity principles to extend the SM, I have tried to convince you that the known neutrinos are Majorana fermions, and their tiny masses originate from the *SEESAW* mechanism. This picture is fully in agreement with the spirit of Weinberg's SMEFT, and thus located in Vafa's landscape of particle physics.**



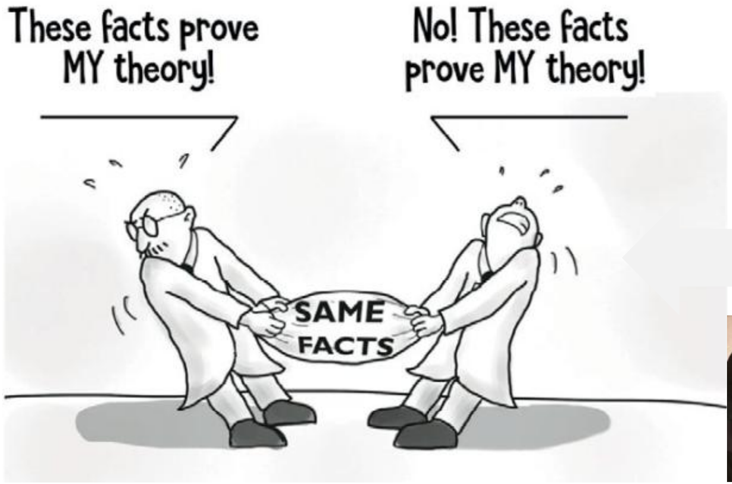
Cumrun Vafa 2005

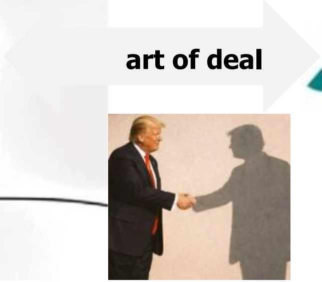


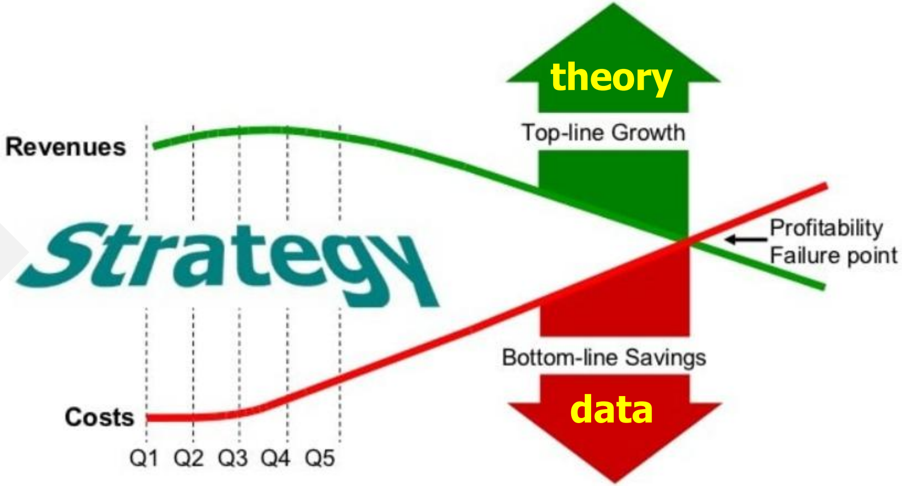
♦ **But this mechanism has no quantitative predictability, nor all the other less interesting scenarios.**

Implication: Data is not King

♦ **To solve or resolve the flavor problems, precision data has been important, but more important is expected to be a brand new theoretical framework to be invented by a real TH genius.**







♦ **I am nothing as compared with W. Pauli, but I have nerve to predict that the genius is among you young talents, as none of you are massless!**

Many Thanks