La fisica delle interazioni deboli

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Giornata a ricordo di
Milla Baldo Ceolin
Sala Rostagni, Padova

Silvia Pascoli

HIDDeν
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

Durham University

INFN
Istituto Nazionale di Fisica Nucleare

CERN

IP3

What are weak interactions?

The Standard Model of particle physics

Gauge group: SU(3) x SU(2) x U(1), with associated gauge bosons. Matter: quarks, leptons in 3 generations. Higgs.

Credit: Andre-Pierre Olivier

$$
\begin{aligned}
\mathcal{L} = &-\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\
&+ i \bar{\psi} \not{D} \psi + h.c. \\
&+ \psi_i y_{ij} \psi_j \phi + h.c. \\
&+ |D_\mu \phi|^2 - V(\phi)
\end{aligned}
$$

Credit: CERN postcard

$$
\mathcal{L}_{\text{gauge}/\psi} = -g_3 A^a_\mu J^{\mu a}_{(3)} - g_2 \left(W^+_\mu J^\mu_{W^+} + W^-_\mu J^\mu_{W^-} + Z_\mu J^\mu_Z \right) - e A_\mu J^\mu_A \, ,
$$

$$
\begin{aligned}
J^{\mu a}_{(3)} &= \bar{u}^i \gamma^\mu T^a_{(3)} u^i + \bar{d}^i \gamma^\mu T^a_{(3)} d^i \\
J^\mu_{W^+} &= \frac{1}{\sqrt{2}} \left(\bar{\nu}^i_{\mathrm{L}} \gamma^\mu e^i_{\mathrm{L}} + V^{ij} \bar{u}^i_{\mathrm{L}} \gamma^\mu d^j_{\mathrm{L}} \right) \\
J^\mu_{W^-} &= (J^\mu_{W^+})^* \\
J^\mu_Z &= \frac{1}{\cos\theta_{\mathrm{W}}} \Big[\frac{1}{2} \bar{\nu}^i_{\mathrm{L}} \gamma^\mu \nu^i_{\mathrm{L}} + \left(-\frac{1}{2} + \sin^2\theta_{\mathrm{W}} \right) \bar{e}^i_{\mathrm{L}} \gamma^\mu e^i_{\mathrm{L}} + (\sin^2\theta_{\mathrm{W}}) \bar{e}^i_{\mathrm{R}} \gamma^\mu e^i_{\mathrm{R}} \\
&\quad + \left(\frac{1}{2} - \frac{2}{3} \sin^2\theta_{\mathrm{W}} \right) \bar{u}^i_{\mathrm{L}} \gamma^\mu u^i_{\mathrm{L}} + \left(-\frac{2}{3} \sin^2\theta_{\mathrm{W}} \right) \bar{u}^i_{\mathrm{R}} \gamma^\mu u^i_{\mathrm{R}} \\
&\quad + \left(-\frac{1}{2} + \frac{1}{3} \sin^2\theta_{\mathrm{W}} \right) \bar{d}^i_{\mathrm{L}} \gamma^\mu d^i_{\mathrm{L}} + \left(\frac{1}{3} \sin^2\theta_{\mathrm{W}} \right) \bar{d}^i_{\mathrm{R}} \gamma^\mu d^i_{\mathrm{R}} \Big] \\
J^\mu_A &= (-1) \bar{e}^i \gamma^\mu e^i + \left(\frac{2}{3} \right) \bar{u}^i \gamma^\mu u^i + \left(-\frac{1}{3} \right) \bar{d}^i \gamma^\mu d^i \, .
\end{aligned}
$$

History of weak interactions physics

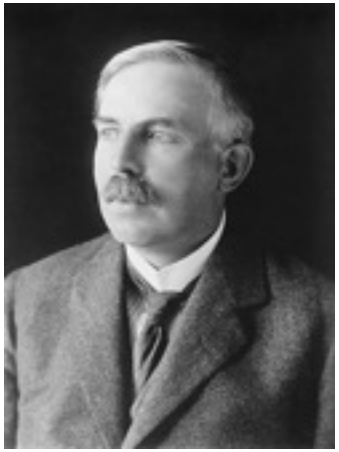
The beginning of weak interactions

The start of weak interaction physics can be taken to be the discovery of radioactivity by Becquerel in 1896, followed by work by Rutherford, M. and P. Curie and others.

H. Becquerel

M. Skłodowska Curie

P. Curie

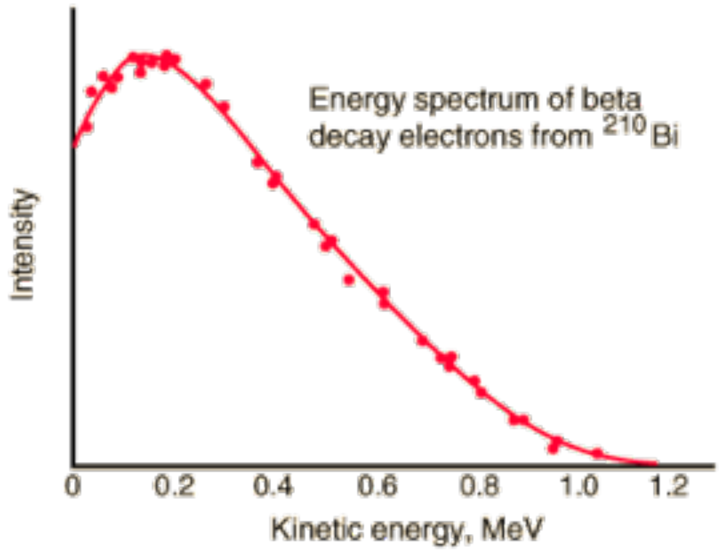


E. Rutherford

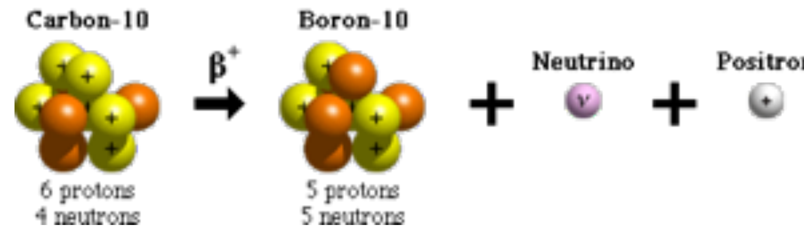
A. Niepce de Saint Victor

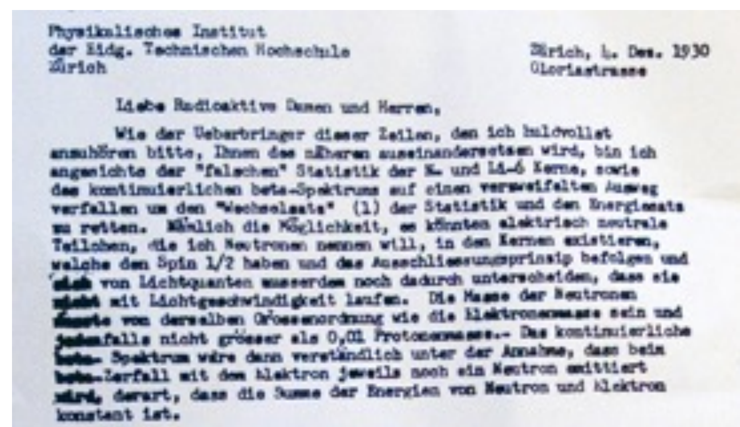
A new type of rays have been found: alpha particles and beta particles, charged and emitted spontaneously by matter in a new type of process.

The subsequent decades were focussed on studying radioactivity properties and the energy emitted in beta decays, by Meitner, Hahn, Wilson, Chadwick, Ellis, Van Baeyer, Bohr and others.



G. J. Neary, Roy. Phys. Soc. , A175, 71 (1940).





Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

Pauli's letter collection, CERN

Proposal of "neutrino" put forward by W. Pauli in 1930.

The Fermi interaction

- The neutron was discovered in 1932 by J. Chadwick.

- Fermi, following E. Amaldi, used the name "neutrino" (little neutron) to indicate Pauli's particle.

- Soon after, he proposed the Fermi theory of beta decay in analogy to electromagnetic interactions.

E. Fermi

$$\mathcal{H} = g[Q\tilde{\psi}^*\delta\varphi + Q^*\tilde{\psi}\delta\varphi^*]$$

E. Fermi, Nuovo Cimento 11, 1 (1934)

Paper rejected by Nature as "it contained speculations too remote from reality to be of interest to the reader".

TENTATIVO DI UNA TEORIA DEI RAGGI β

Nota (¹) di Enrico Fermi

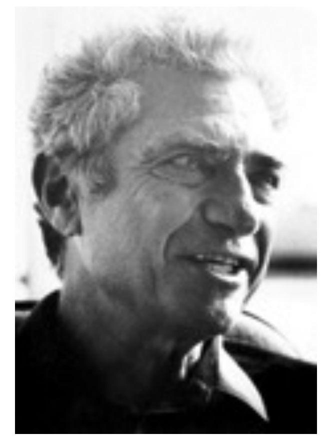
Sunto. - *Si propone una teoria quantitativa dell'emissione dei raggi β in cui si ammette l'esistenza del « neutrino » e si tratta l'emissione degli elettroni e dei neutrini da un nucleo all'atto della disintegrazione β con un procedimento simile a quello seguito nella teoria dell'irradiazione per descrivere l'emissione di un quanto di luce da un atomo eccitato. Vengono dedotte delle formule per la vita media e per la forma dello spettro continuo dei raggi β, e le si confrontano coi dati sperimentali.*

A zoo of particles

- In the later '30 and '40 new particles were discovered. The charged and neutral pions, the muons (Conversi, Pancini, Piccioni's experiment, work by Rastelli, Rossi et al., by Lattes, Muirhead, Occhialini, Powell).

Archivio Conversi

- It was soon realised that muons decay in 3 states (J. Steinberger) and that this process can be described by a Fermi Universal interaction.



J. Steinberger

- Other particles: KL and KS, Lambda…

"Nuclear Interactions of Neutral K-Mesons of Long Lifetime," Nuovo Cimento, 6:130 (1957), M. Baldo Ceolin et al; "Anti-Lambda Hyperon," Phys. Rev. Lett., 1:179 (1958), M. Baldo Ceolin and D.J. Prowse.

Discrete symmetries and their violation

- The theta-tau puzzle led to the realisation that parity is not conserved in weak interactions.

- 1956: Theory of P violation (Lee and Yang).

- 1956: M.me Wu's experiment: P and C violation. Neutrinos come only as left-handed differently from all other fermions.

- 1964: CP violation (Cronin and Finch)

M.me Wu

- V-A structure and its formulation of current x current (Sudarshan, Marshak, Feynman, Gell-mann et al.)

Gauge theory and the Standard Model

- 1961: SU(2)xU(1) gauge group description of weak interactions (Glashow)

- 1961: Spontaneous symmetry breaking (Goldstone; Nambu, Jona-Lasinio)

- 1964-1967 Abelian and nonabelian Higgs mechanism (Higgs, Brout, Englert, Guralnik, Hagen, Kibble)

- 1967: Electroweak theory (Salam, Weinberg). Its renormalisability was proved by t'Hooft and Veltman.

S. Glashow

P. Higgs

A. Salam

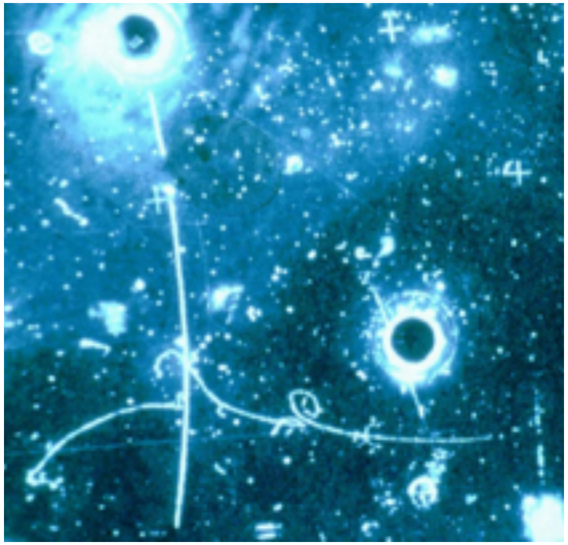
S. Weinberg

The discovery of NC weak interactions

- 1973 Gargamelle reported 166 hadronic NC events and 1 e NC event from a wide beam from PS.

- '70s: NUE (Aachen-Padua) experiment. Sparks chamber behind Gargamelle to study neutrino electron interactions. *"Measurement of Muon-Neutrino and Antineutrino Scattering off Electrons," Phys. Rev. Lett., 41:213-216 (1978), H. Faissner,… M. Baldo Ceolin et al.*

- 1983: Discovery of the W and Z bosons by UA1 and UA2 using the CERN proton-antiproton collider (C. Rubbia et al.)



Gargamelle leptonic NC event

NUE experiment

The problem of flavour

N. Cabibbo

- 1963 Mixing in the quark sector and the Cabibbo angle restoring universality in weak interactions

- 1962 Maki, Nakagawa, Sakata: 3 family mixing

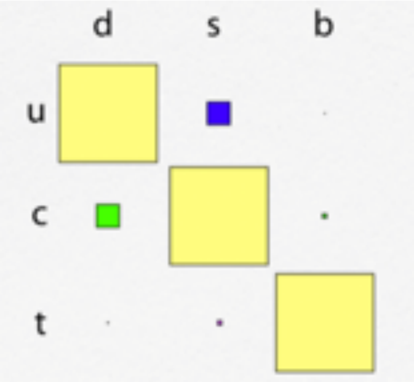
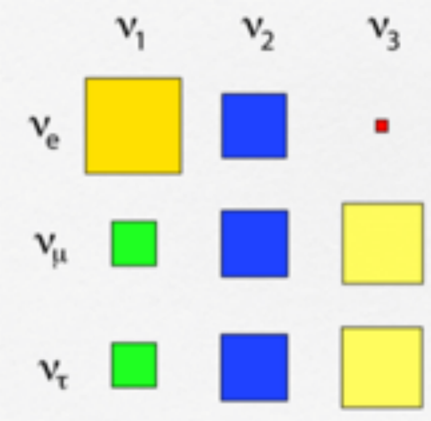


Image credit: S. King

- 1970 FCNC and the GIM mechanism and the prediction of a 4th quark

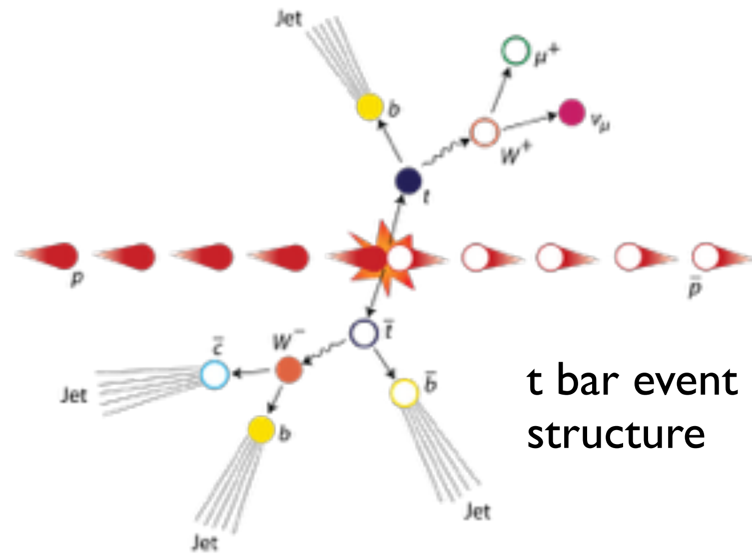


- 1973: CKM matrix (Kobayashi, Maskawa)

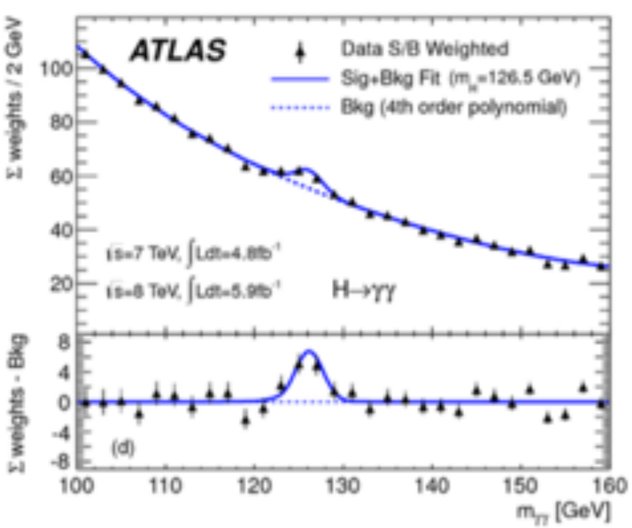
- 1974: discovery of the c quark

Completing the picture

- 1975 tau lepton discovery
- 1995 Top discovery
- 2000 Tau neutrino discovery (DONUT)
- 2012 Higgs discovery

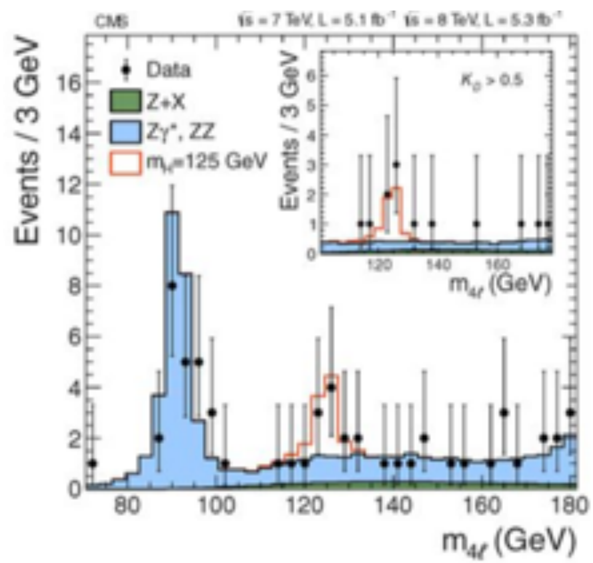


t bar event structure



ATLAS collaboration

CMS collaboration



Zooming in on the Standard Model: precision observables

- 1989-: Precision measurements of weak interactions and properties led by e+e- collider experiments at the Z0 resonance, LEP at CERN, and SLD, a SLAC.

- 1987-: Hadron colliders, Tevatron at Fermilab and LHC at CERN.


SLD

LEP

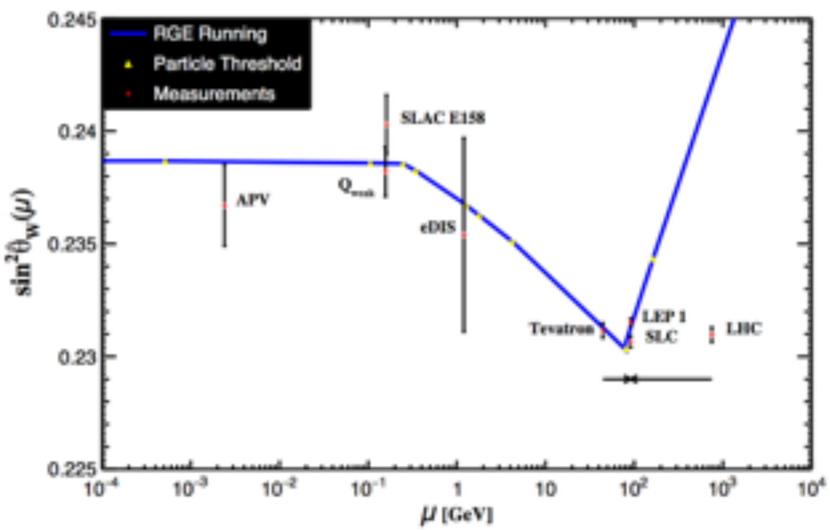
Tevatron

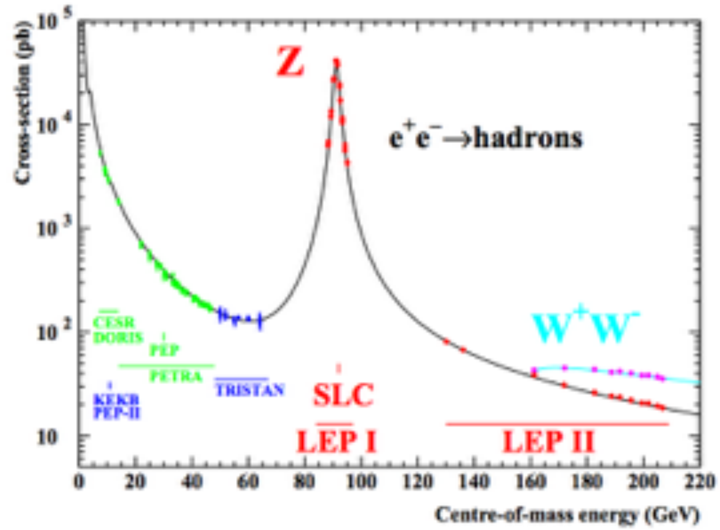

LHC

They studied the W and Z bosons and gauge self-interactions, determined with precision the mass of the W and top, and carried out precision tests of the SM (including K, B and D decays).

• The SM is correct at 0th order: the gauge principle, the gauge group, the fermionic representations, the presence of a scalar.

• SM is accurate at the loop level: theory is renormalisable, running of parameters and predictions.





PDG

• TeV new physics is strongly constrained.

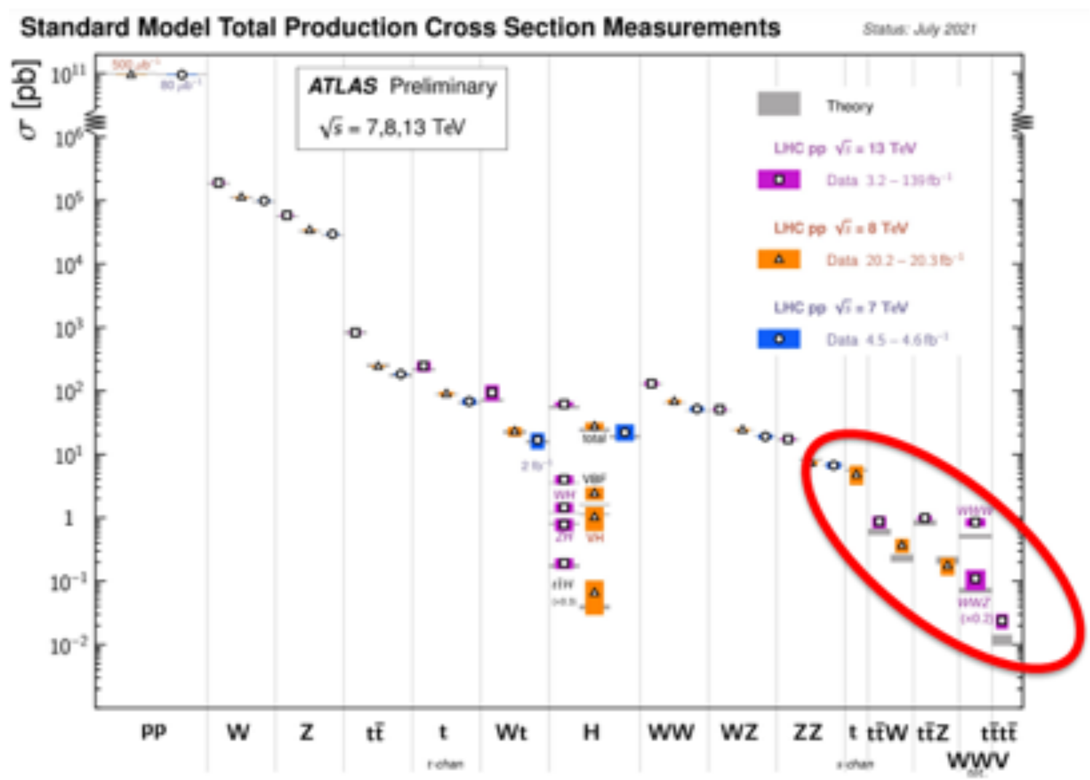
What are the open questions?
What do still need to establish about weak interactions?

EW symmetry breaking and the gauge structure

- The Higgs is the least known component of the SM. Is it a fundamental scalar? Why is it light (hierarchy problem)?

- Test the Higgs mechanism: need to reconstruct the Higgs potential and observe/study VVH, VVHH, VVVH.

- Test gauge boson interactions



ATLAS Collaboration, J. Metcalfe, EPS-HEP 2021

Conservation laws

- B and L appear conserved in the SM, at the perturbative level. Are they fundamental symmetries?

B and L related to key issues BSM:

- GUT theories;
- origin of neutrino masses;
- generation of the baryon asymmetry of the Universe.

Their violation induces proton decay and n-nbar oscillations. L violation would imply Majorana neutrinos and can be tested in neutrino less double beta decay.

"A New Experimental Limit on Neutron-Antineutron Oscillations," Zeit.für Physic C, C63:409-416, (1994), M. Baldo Ceolin et al.

The problem of flavour

Why there are 3 generations is a mystery. Why is there P, C and CP violation?

Not surprisingly, there is mixing and it is different in the quark and lepton sector.

Why mixing has "special values"? Masses and the mixing matrix arises from the diagonalisation of the fermionic mass matrix. For instance, for neutrinos:

$$\boxed{M_M = (U^\dagger)^T m_{\rm diag} U^\dagger} \quad \Rightarrow \quad \boxed{n_L = U^\dagger \nu_L}$$

Theory

$$\mathcal{L}_{CC} = \frac{g}{\sqrt{2}} (\bar{e}_L, \bar{\mu}_L, \bar{\tau}_L) \gamma^\mu U_{\rm osc} \begin{pmatrix} \nu_{1L} \\ \nu_{2L} \\ \nu_{3L} \end{pmatrix} W_\mu \qquad \text{with} \qquad U_{\rm osc} = V_L^\dagger U_\nu$$

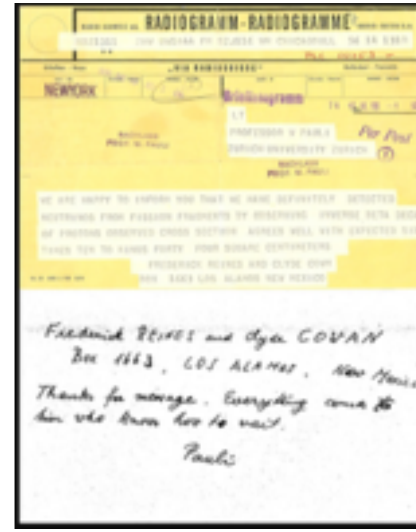
Symmetry as well as other (e.g. anarchy) approaches are being pursued. A guiding principle is still missing.

Neutrinos and their physics: the weak particles "per excellence"

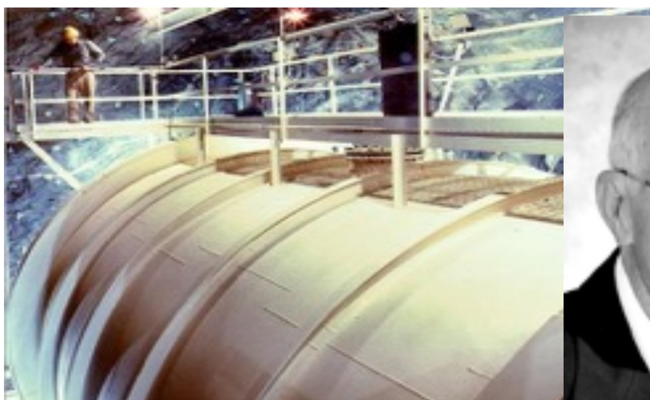
An history within: neutrinos in SM and beyond

- Reines and Cowan discovered neutrinos in 1956 using inverse beta decay.
- Muon neutrinos were found in 1962 by L. Lederman, M. Schwartz and J. Steinberger.

F. Reines

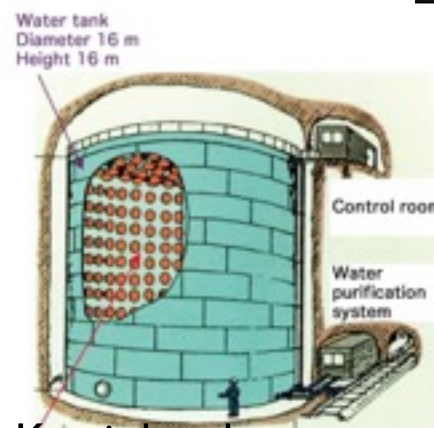

RADIOGRAMM-RADIOGRAMME
NEWYORK

Frederick Reines and Clyde Cowan
Box 1663, Los Alamos, New Mexico
Thanks for message. Everything comes to him who knows how to wait.
Pauli



The Homestake experiment

R. Davis Jr.



Kamiokande

M. Koshiba

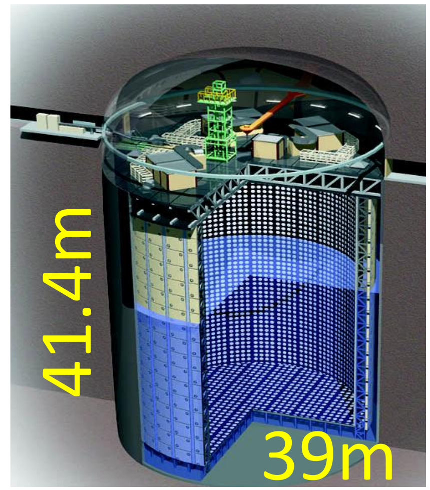
Searches were performed for astrophysical neutrinos, produced in the Sun, Supernova and in the atmosphere (discovered in 1965 by KGF and Reines' exp).

Anomalies in astrophysical neutrinos started to emerge.

- First indications of ν oscillations came from solar ν: less electron neutrinos were observed than expected.

SNO

A. McDonald

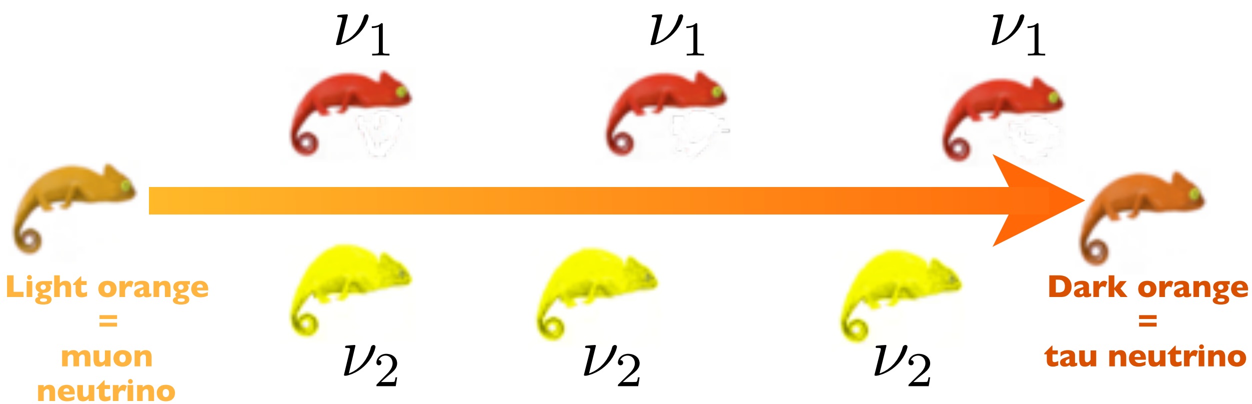


Super-Kamiokande

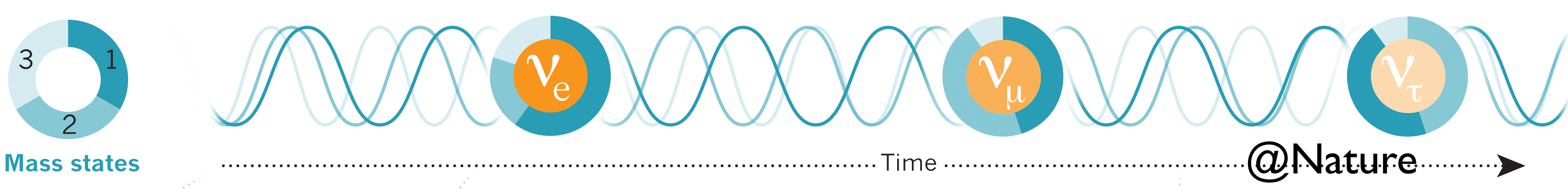
T. Kajita

- Indications of an anomaly in atmospheric neutrinos was presented in 1988, subsequently confirmed by MACRO.
- More muon neutrinos were seen going down than coming up from the other side of the Earth.
- Discovery was presented in 1998 by SuperKamiokande.

The first idea of neutrino oscillations was put forward by B. Pontecorvo in 1957.

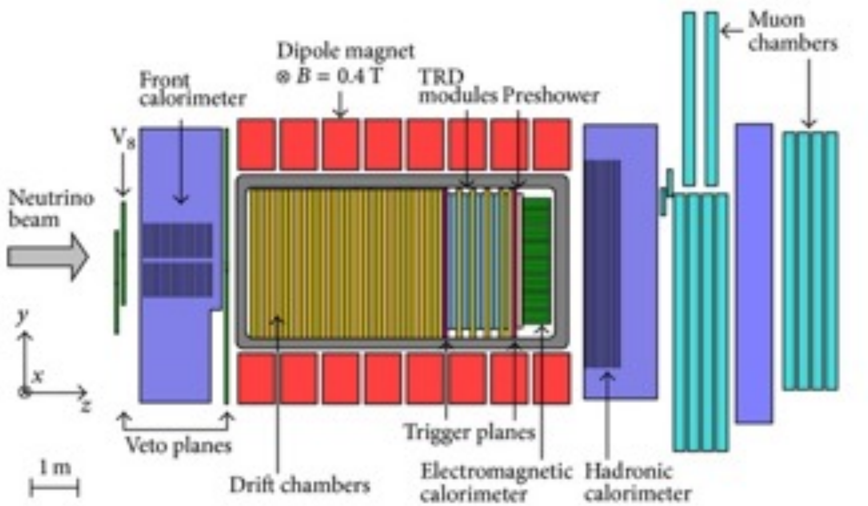


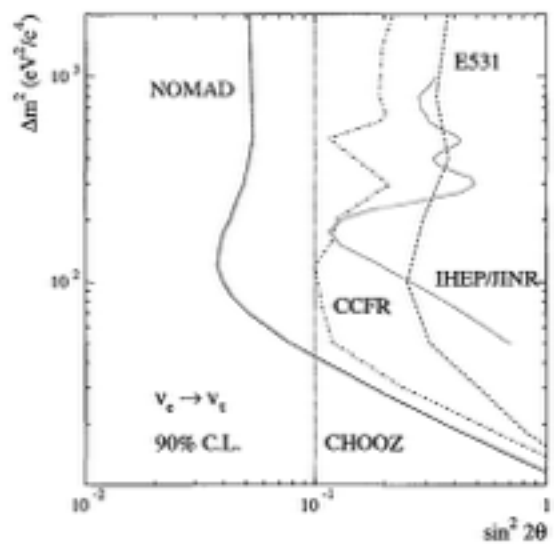
A flavour neutrino is a superposition of different mass states. If their mass is different, then they will evolve in time differently and later their combination can correspond to a different type of neutrino.



Searches for nu oscillations 80'-90': BEBC and NOMAD

NOMAD run in 1995-1998 using the CERN WANF WBB beam and a 2.7 tons target with magnetisation. The goal was to search for muon to tau neutrino oscillations, for a mass in the eV range. It collected ~1000000 CC events.

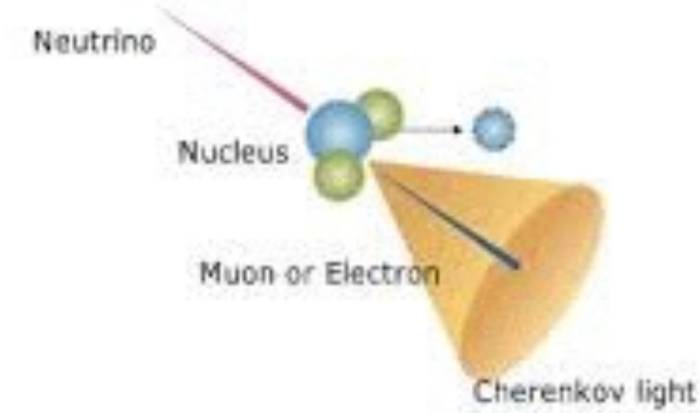




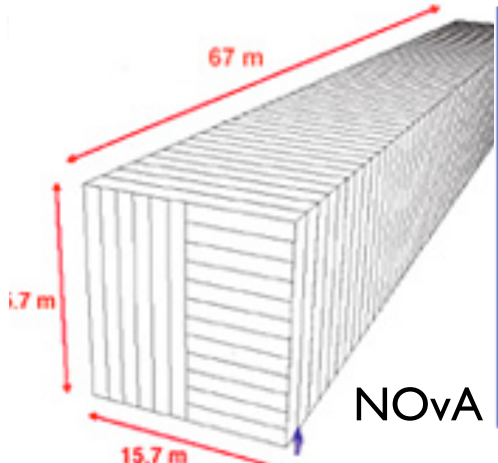
NOMAD collaboration

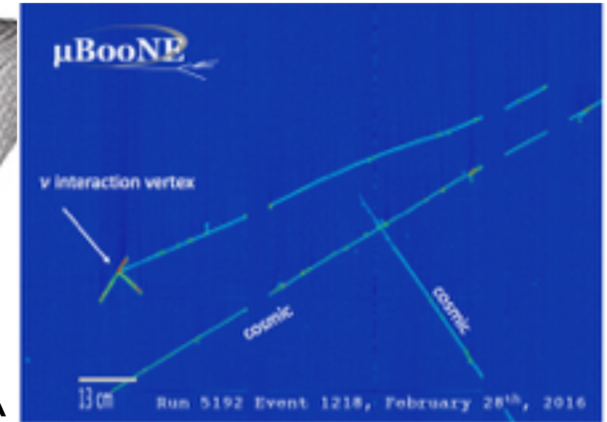
The bounds remain among the most stringent in the tau neutrino sector (the least known). *"Limit on ve ---> vT Oscillations from the NOMAD Experiment," Phys. Lett., B471:406-410*

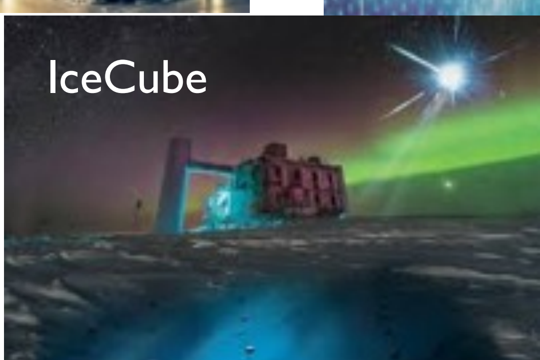
Studies of nu oscillations >2000

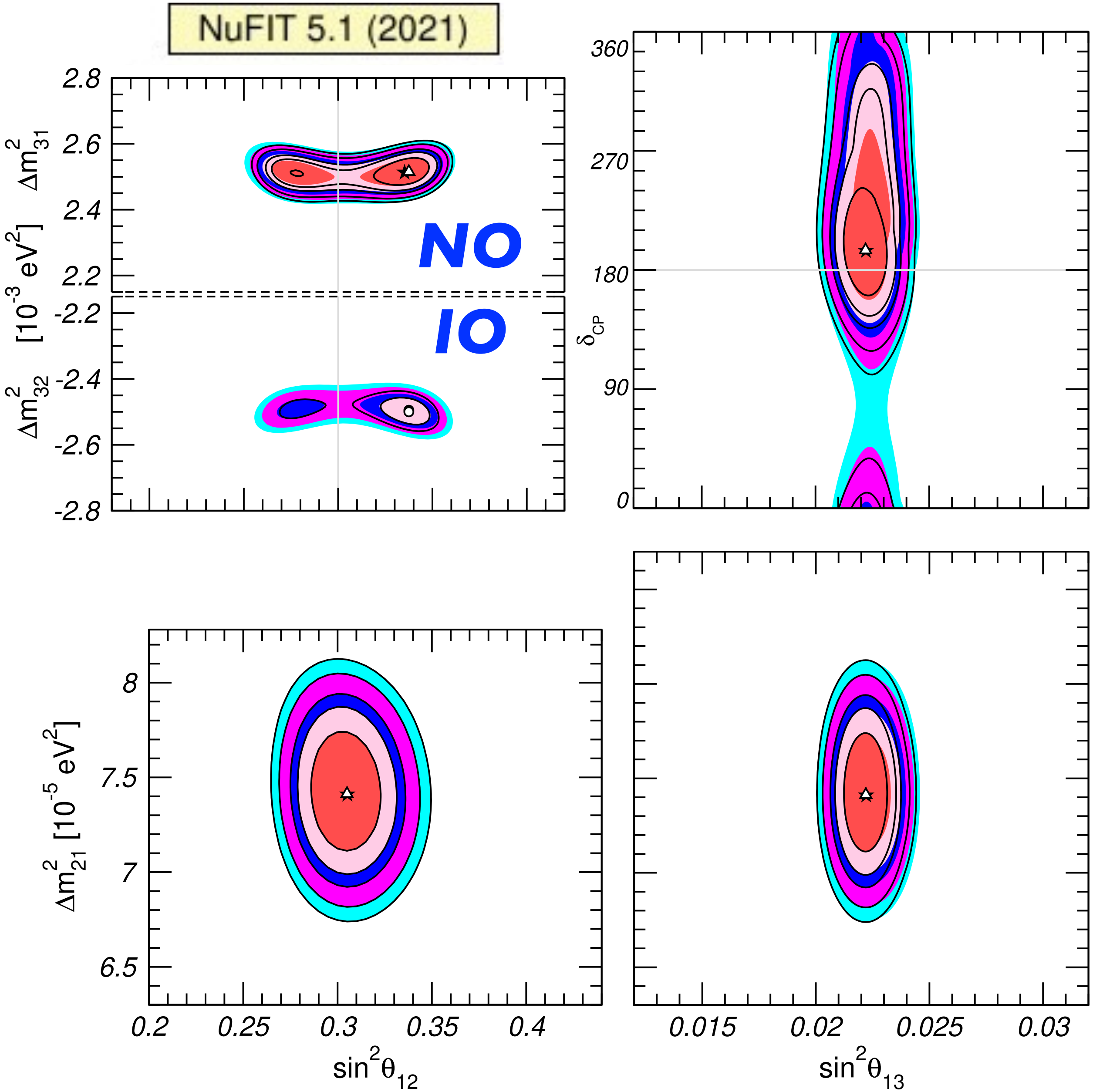


Credit: Super-Kamiokande









Current knowledge of neutrino properties:

- 2 mass squared differences
- 3 sizable mixing angles,
- hints of CPV?
- mild indications in favour of NO

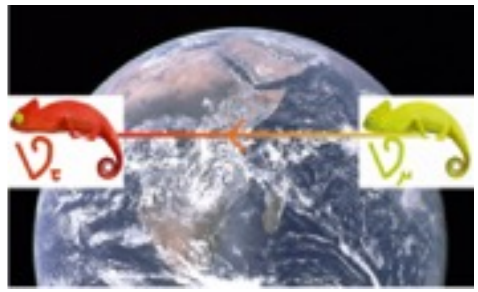
http://www.nu-fit.org/ M. C. Gonzalez-Garcia et al., 2007.14792

What are the open questions? BSM and Weaker than weak interactions

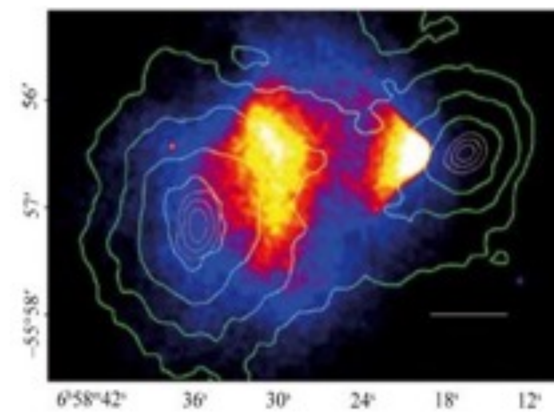
Evidence beyond the SM

There is experimental/observational evidence that the Standard Model is incomplete.

Neutrino masses



Dark Matter



Clowe et al.

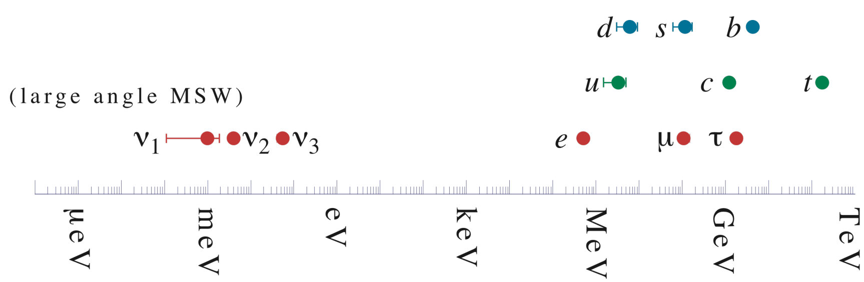
@Symmetry magazine

Baryon asymmetry

Neutrinos: Open window on Physics BSM

Neutrinos give a new perspective on physics BSM.

1. Origin of masses



Why neutrinos have mass? and why are they so much lighter than the other fermions? and why their hierarchy is at most mild?

2. Problem of flavour

$$\begin{pmatrix} \sim 1 & \lambda & \lambda^3 \\ \lambda & \sim 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & \sim 1 \end{pmatrix} \quad \lambda \sim 0.2$$

$$\begin{pmatrix} 0.8 & 0.5 & 0.16 \\ -0.4 & 0.5 & -0.7 \\ -0.4 & 0.5 & 0.7 \end{pmatrix}$$

Why leptonic mixing is so different from quark mixing?

This information is **complementary** with the one from flavour physics experiments and from colliders.

Neutrino masses Beyond SM

In the SM, neutrinos do not acquire mass and mix.

Dirac Masses

If we introduce a right-handed neutrino, then an interaction with the Higgs boson emerges.

$$\mathcal{L} = -y_\nu \bar{L} \cdot \tilde{H} \nu_R + \text{h.c.} \longrightarrow m_D = y_\nu v = V m_{\text{diag}} U^\dagger$$

This term is SU(2) invariant and respects lepton number.

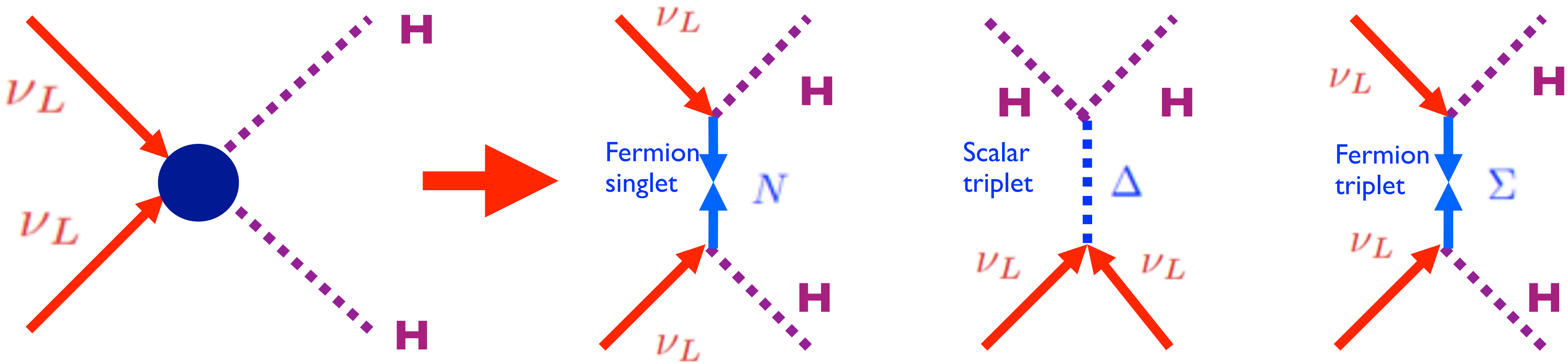
- why the coupling is so small??? $y_\nu \sim \frac{\sqrt{2} m_\nu}{v_H} \sim \frac{0.2 \text{ eV}}{200 \text{ GeV}} \sim 10^{-12}$
- why the leptonic mixing angles are large?
- why neutrino masses have at most a mild hierarchy?
- why no Majorana mass term for RH neutrinos? We need to impose L as a fundamental symmetry (BSM).

Majorana Masses

In order to have an SU(2) invariant mass term for neutrinos, it is necessary to introduce a Dimension 5 operator (or to allow new scalar fields, e.g. a triplet):

$$-\mathcal{L} = \lambda \frac{L \cdot H L \cdot H}{M} = \frac{\lambda v_H^2}{M} \nu_L^T C^\dagger \nu_L$$

Weinberg operator, PRL 43



Minkowski, Yanagida, Glashow, Gell-Mann, Ramond, Slansky, Ma, Mohapatra, Senjanovic, Magg, Wetterich, Lazarides, Shafi, Schecter, Valle, Hambye…

This term breaks lepton number and induces Majorana masses and Majorana neutrinos. It can be induced by a high energy theory (see-saw mechanism).

Neutrino masses BSM: "vanilla" see saw mechanism type I

Particle zoo

Symmetry magazine

- Introduce a right handed neutrino N
- It couples to the Higgs and has a Majorana mass

$$\mathcal{L} = -Y_\nu \bar{N} L \cdot H - 1/2 \bar{N}^c M_R N$$

$$\begin{pmatrix} 0 & m_D \\ m_D^T & M_N \end{pmatrix} \Rightarrow m_\nu = \frac{Y_\nu^2 v_H^2}{M_N} \sim \frac{1\ \mathrm{GeV}^2}{10^{10}\mathrm{GeV}} \sim 0.1\ \mathrm{eV}$$

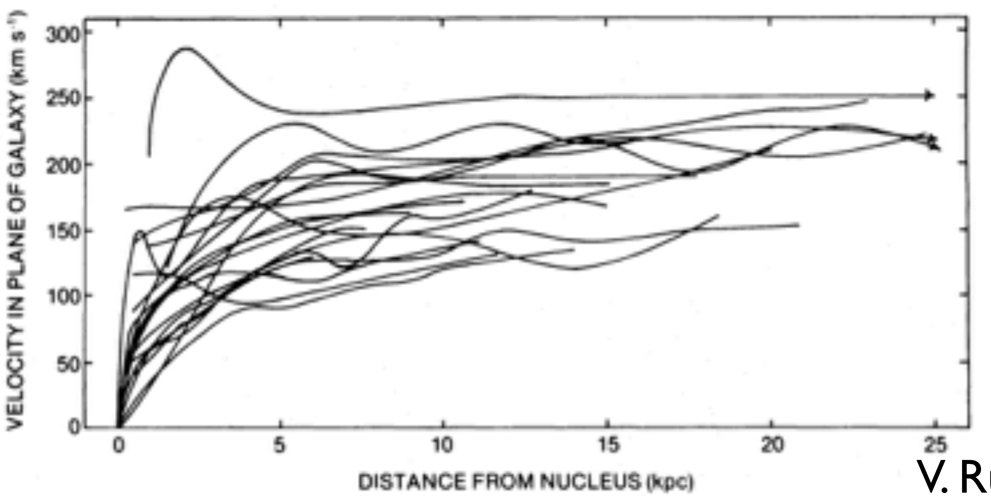
Minkowski; Yanagida; Glashow; Gell-Mann, Ramond, Slansky; Mohapatra, Senjanovic

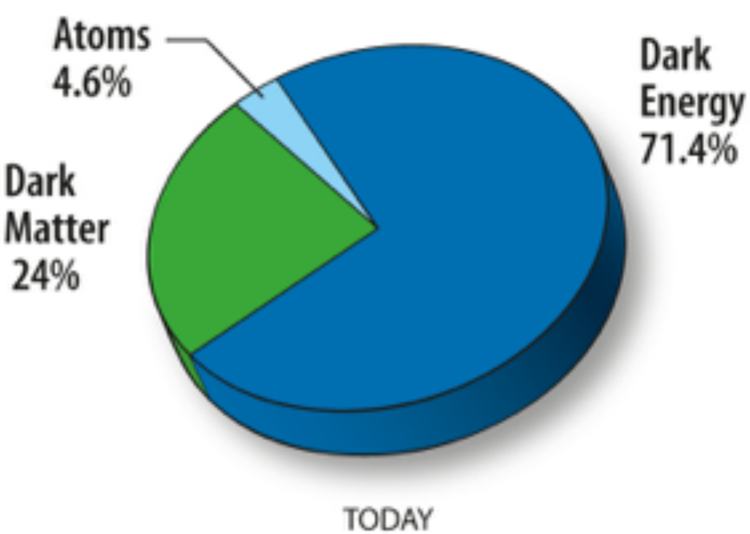
As a result, neutrinos can have naturally small masses and are Majorana particles.

Dark Matter

In the '30s, first hints of DM were found by F. Zwicky when he studies the Coma Cluster. Galaxy Rotation curves indicating that there is a matter component outside the visible disk. Information from CMB, lensing, LSS formation.

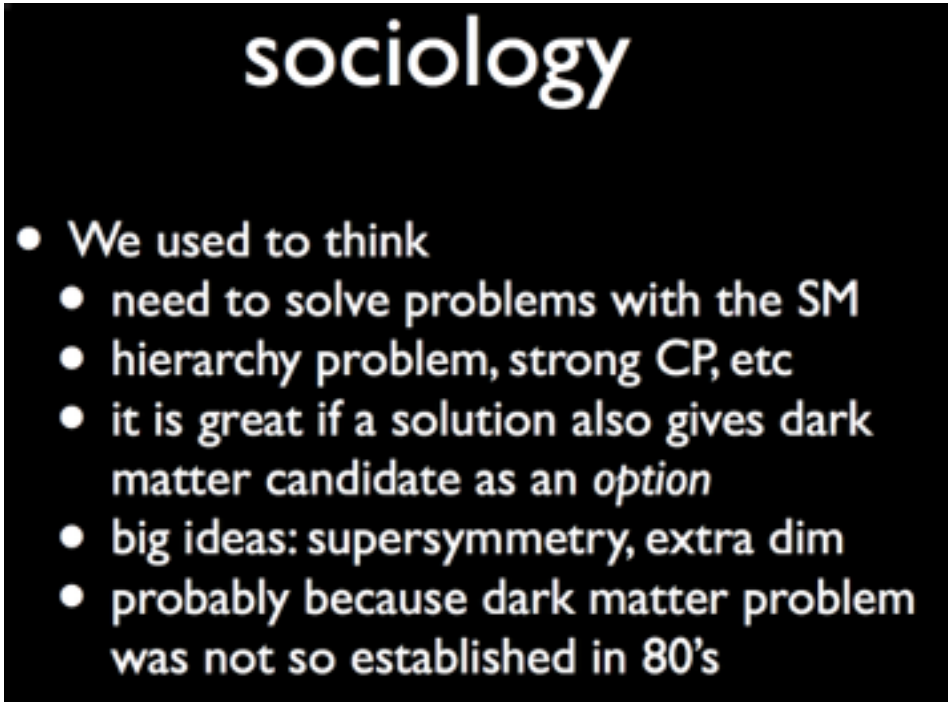
Coma Cluster





V. Rubin et al., Astrophys. J. 238 (1980)

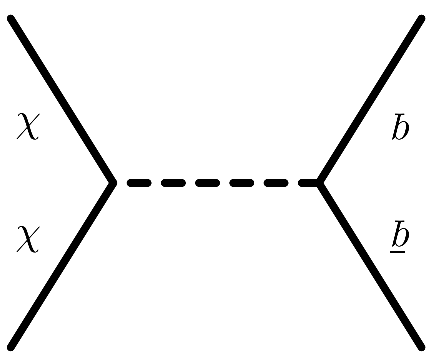
Review of dark matter candidates: from the lamppost to a wide landscape



H. Murayama, Granada symposium 2019

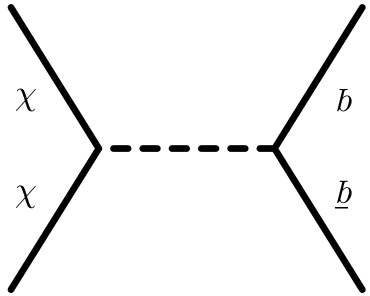
WIMP miracle:
weak coupling
weak masses

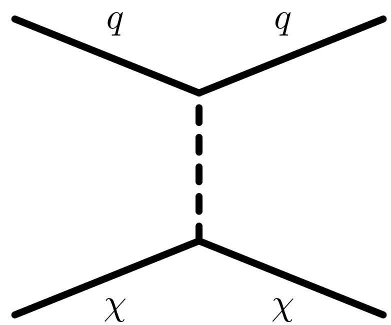
Right abundance via freeze-out

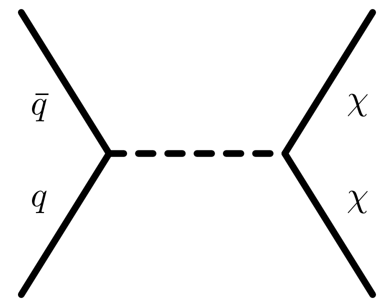


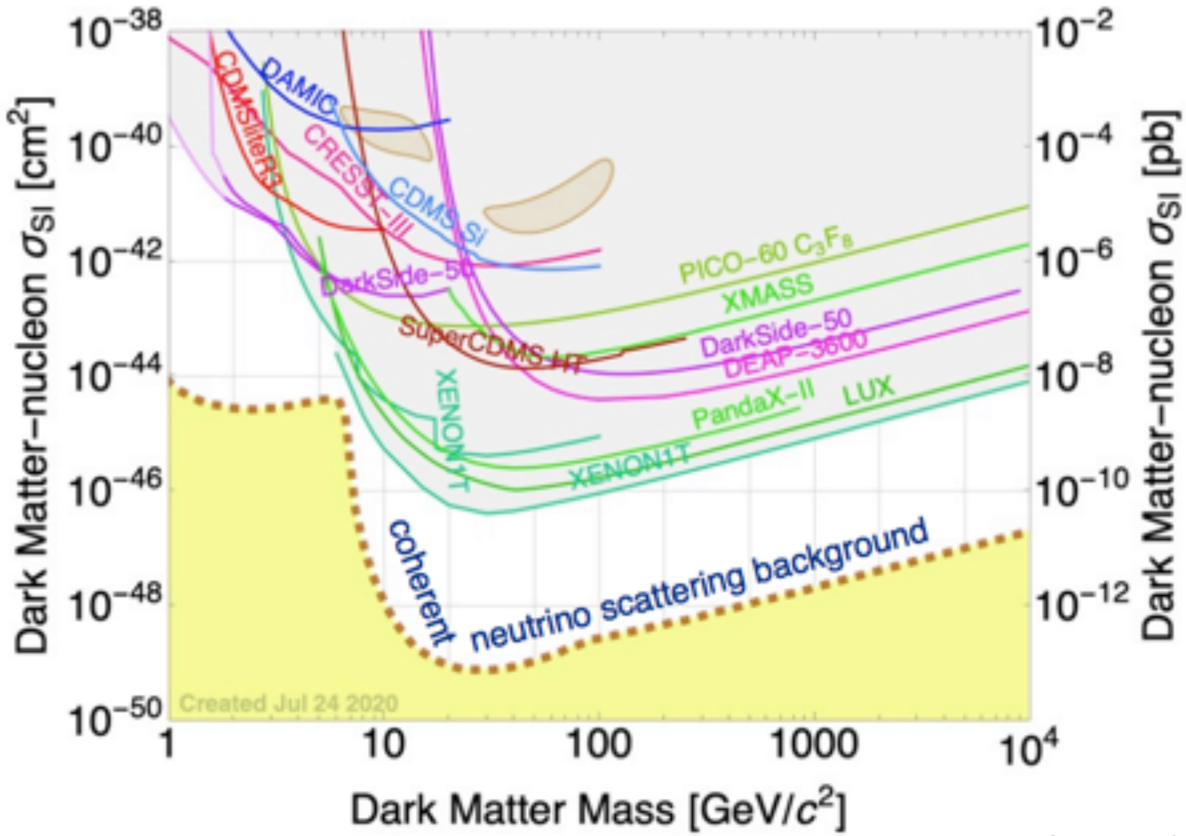
$$\sigma_{\chi\chi} \sim g^4 \frac{m_{DM}^2}{m_V^4} \sim 10^{-8}\ \mathrm{GeV}^{-2}$$

for $g \sim 0.3, m_{DM}, m_V \sim 100\ \mathrm{GeV}$









So far, no direct or indirect evidence of DM properties.

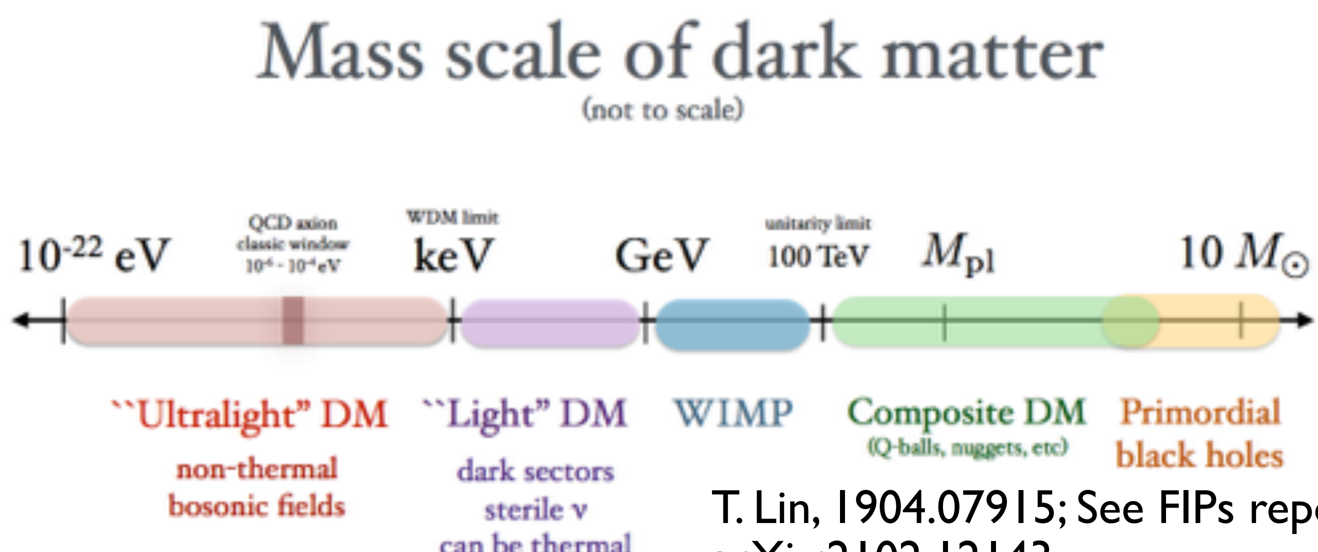
L. Hsu, ICHEP 2020

new sociology

- WIMP should be explored at least down to the neutrino floor
  - heavier? e.g., wino @ 3TeV
- dark matter definitely exists
  - naturalness problem may be optional?
- need to explain dark matter on its own
- perhaps we should decouple these two
- do we really need big ideas like SUSY?
- perhaps not necessarily heavier but rather lighter and weaker coupling?

H. Murayama, Granada symposium 2019

Let's rethink particle DM:
- interacts gravitationally;
- it is dark (no significant charge);
- has only weak interactions with the SM;
- it needs to cluster (cold or warm).



T. Lin, 1904.07915; See FIPs report: arXiv:2102.12143.

The baryon asymmetry of the Universe

There is evidence of the baryon asymmetry:

$$\eta_B \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.18 \pm 0.06) \times 10^{-10}$$

Planck, 1502.01589, AA 594

In order to generate it dynamically in the Early Universe, the Sakharov's conditions need to be satisfied:

- B (or L) violation;
- C, CP violation;
- departure from thermal equilibrium.

$$X^c \to \bar{q}q \qquad X \to \bar{q}q$$
$$X \to \ell q \qquad X^c \to \bar{\ell}\bar{q}$$
$$X \to \bar{q}q \qquad X \to \ell q$$

The Standard Model cannot generate the necessary amount of baryon asymmetry: BSM physics, e.g. electroweak baryogegesis and leptogenesis.

Leptogenesis

- At T>M,
N are in equilibrium:

$$N \leftrightarrow \ell H \quad N \leftrightarrow \ell H \quad N \leftrightarrow \ell H$$
$$N \leftrightarrow \ell H \quad N \leftrightarrow \ell H$$

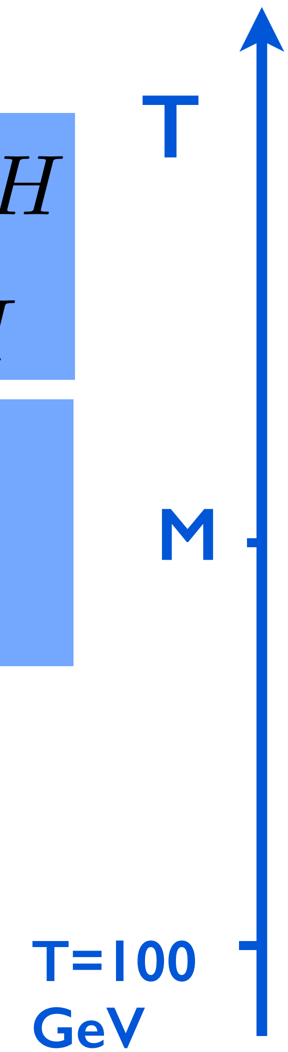
- At T<M,
N drops out of equilibrium:

$$N \to \ell H \quad N \to \ell^c H^c \quad N \to \ell H$$
$$N \to \ell^c H^c \quad N \to \ell^c H^c$$

- A lepton asymmetry can be generated if

$$\Gamma(N \to \ell H) \neq \Gamma(N \to \ell^c H^c)$$

- $$\Delta L \xrightarrow{sphalerons} \Delta B$$



The observation of L violation and of CPV in the lepton sector would be a strong indication (even if not a proof) of leptogenesis as the origin of the baryon asymmetry.

New physics scale? Going to high energy

T=10^{19} GeV

T=10^{14} GeV

- Gravity?
- GUTs? SO(10), SU(5)…

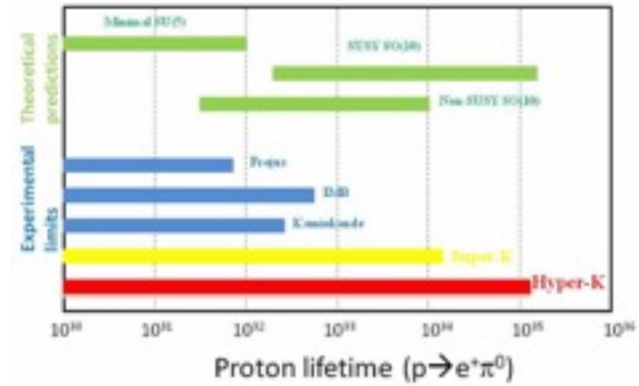
Neutrino masses
Leptogenesis

- SUSY?

T=100 GeV

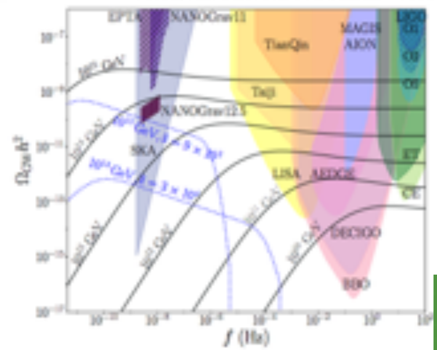
- SMEFT
- SM

EW baryogenesis
Dark matter



Proton decay

Hyper-K

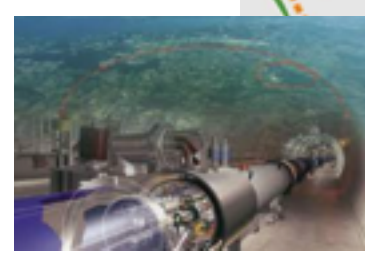


GW

S. King et al., PRL 126 (2021)

FCC-hh

LHC



DM searches, LFV exp

Going low in energy: Dark sectors

- UV completion?

T=100 GeV

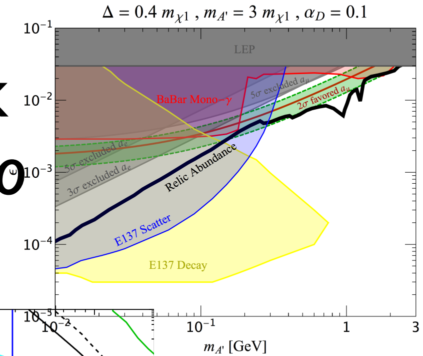
- SM

HNLs

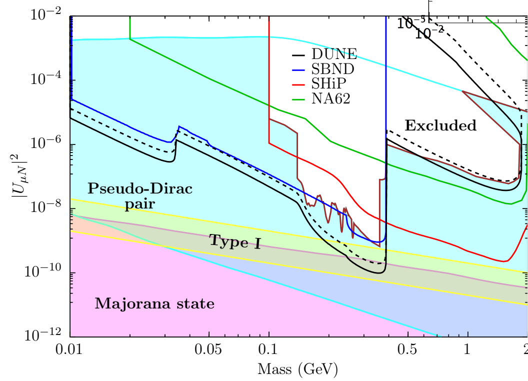
sterile neutrinos

FIMPs

Dark photons

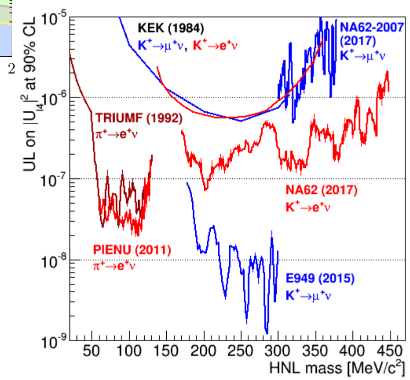


G. Mohlabeng, PRD99 (2019)

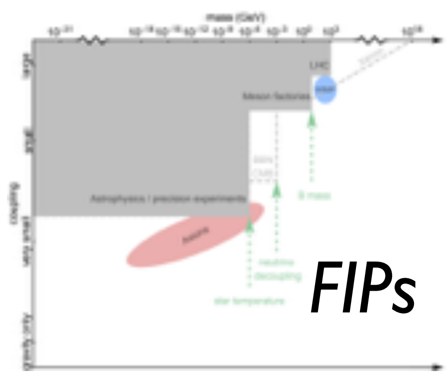


HNLs

Ballett, Boschi, SP, 1905.00284



NA62 Coll., 2017



FIPs

It is possible to construct minimal models, e.g. NuSM (3 RH neutrinos), or full models with richer phenomenology.

The dark or hidden sector indicate extensions of the SM that are below the electroweak scale. They can involve new gauge interactions, scalars and fermions.

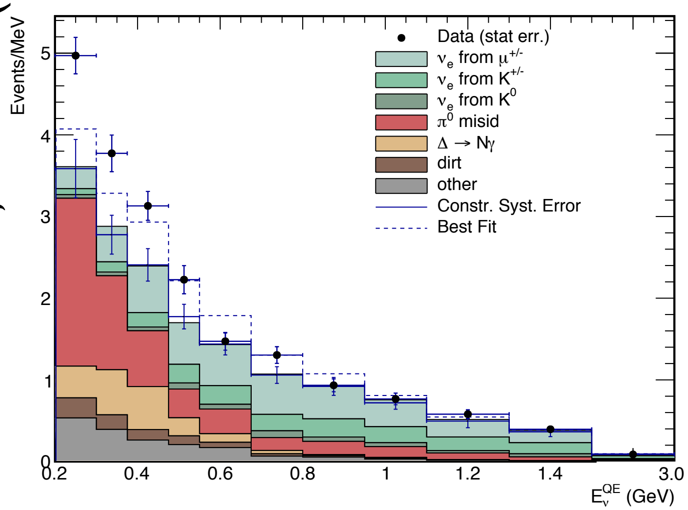
The dark sector interacts with SM via so-called portals:

Portal	Coupling
Dark Photon, A'	$-\frac{\varepsilon}{2\cos\theta_W}F'_{\mu\nu}B^{\mu\nu}$
Axion-like particles, a	$\frac{a}{f_a}F_{\mu\nu}\tilde{F}^{\mu\nu}$, $\frac{a}{f_a}G_{i,\mu\nu}\tilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$
Dark Higgs, S	$(\mu S + \lambda_{\rm HS}S^2)H^\dagger H$
Heavy Neutral Lepton, N	$y_N LHN$
milicharged particle, χ	$\epsilon A^\mu \bar{\chi}\gamma_\mu\chi$

FIPs report, 2102.12143

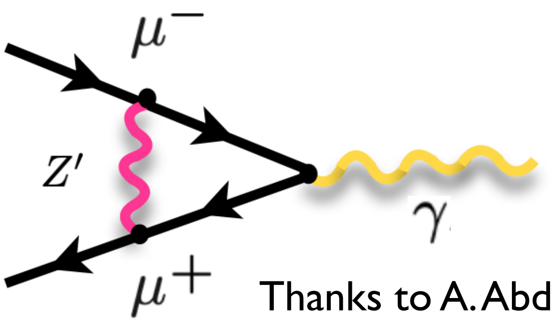
Possible hints?

MiniBooNE Coll., PRL 121 (2018)



MiniBooNE found an excess of events at low energy. First results from MicroBooNE. It is unlikely due to SM photons or to neutrino oscillations.

$$\Delta a_\mu \equiv a_\mu^{exp} - a_\mu^{th} = (274 \pm 73) \times 10^{-11}$$



Thanks to A. Abdullahi

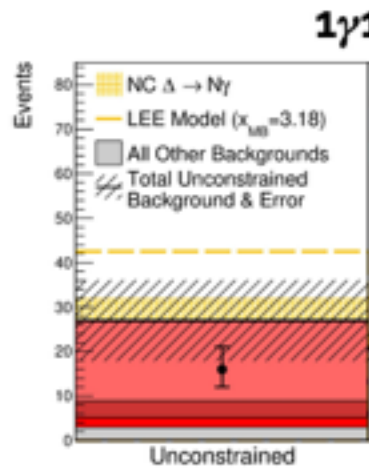
There is a longstanding discrepancy between the measured value of a_μ and the theoretical prediction, at 3.8 sigma.

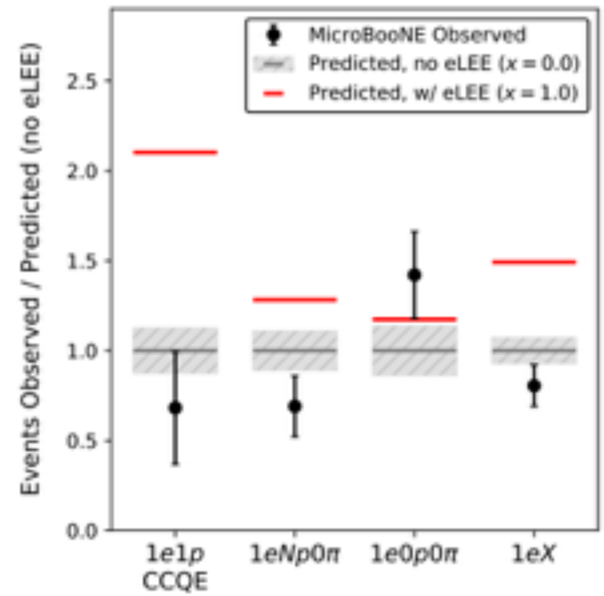
P. Fayet, PRD75 (2007), M. Pospelov, PRD80 (2009)

There are additional anomalies: XENON results, Beryllium (Atomki) anomaly, “Babar mono photon excess”. Light dark photons could provide an explanation.

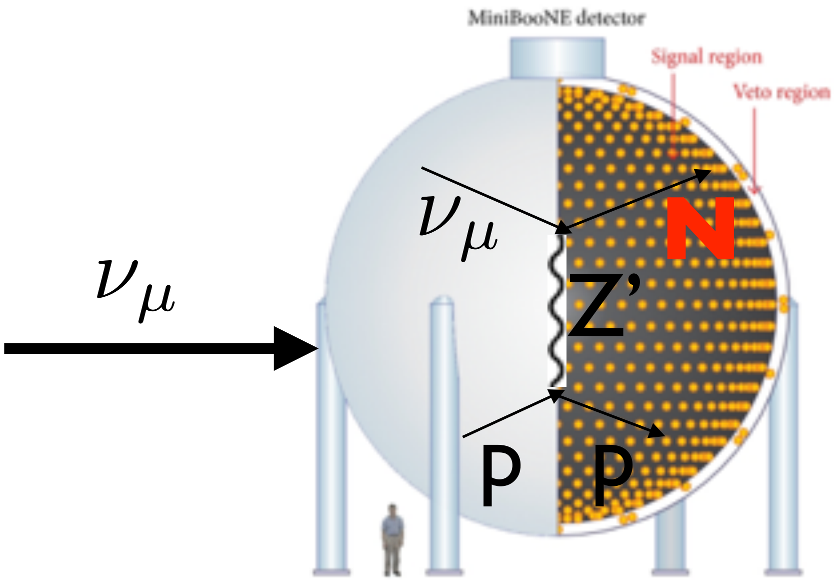
First results from MicroBooNE. It is unlikely the MiniBooNE LEE is due to SM photons and to neutrino oscillations due to sterile neutrinos.

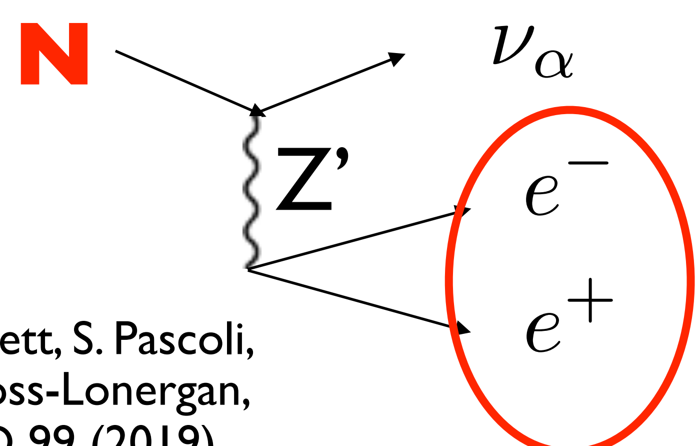
M. Ross-Lonergan's talk at Fermilab, 04/10/2021





MicroBooNE Coll., 2110.00409





P. Ballett, S. Pascoli, M. Ross-Lonergan, PRD 99 (2019)

Un caro ricordo di
Milla Baldo Ceolin

Signora, Professoressa e Scienziata d’eccezione