# Weak interactions studies with a strong team at TRIUMF

Jean-Michel Poutissou

Senior scientist emeritus

CAP congress Halifax 2018

Weak interactions at TRIUMF?

- R.Feynman visited TRIUMF in the winter of 1974.
- I showed him the beginning of BI1A, I was building with John Vincent.
- He asked me what I was going to do with it and I answered studying the weak interaction.
- He shuddered and said : At that low an energy?
- I don't remember if I answered *" you surely must be joking Dr. Feynman "* but…. I should have .

- Anyway we did start a program in muon and pion decay parameters measurement, life time, and rare decays etc.

ELEMENTARY PARTICLES
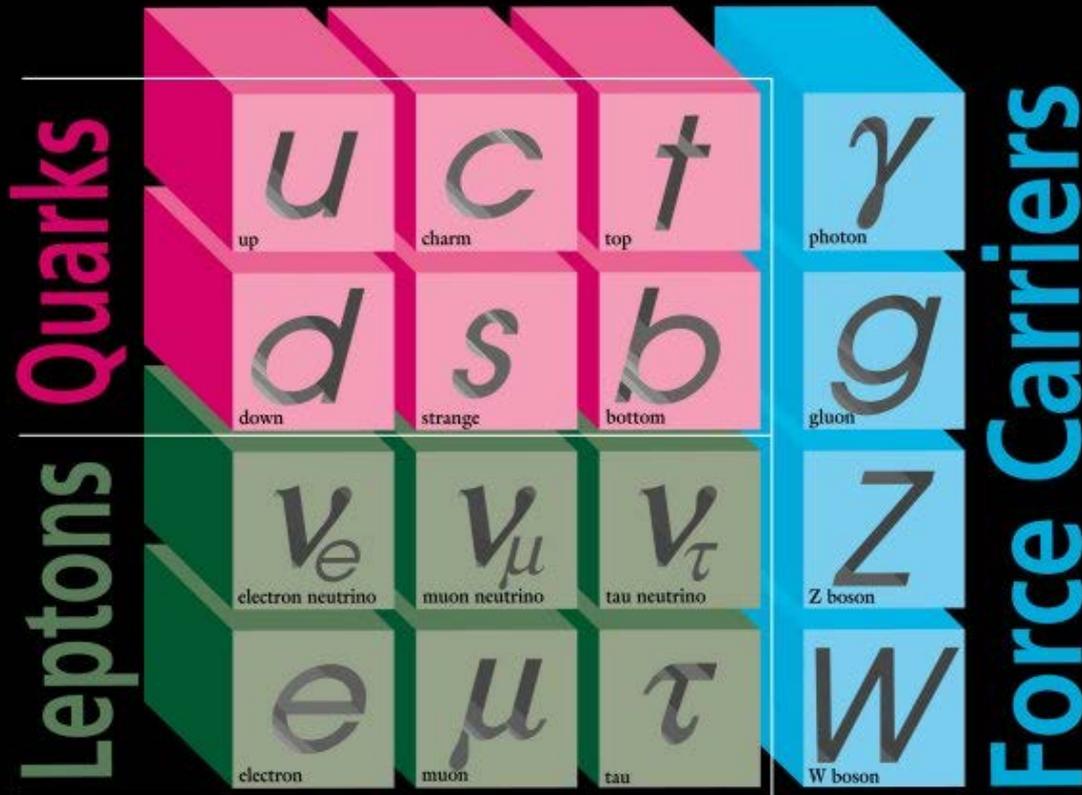
Three Generations of Matter

I II III

The early years

Early μ Decay Measurements

The Absorption of Charged Particles from the 2.2-μsec. Meson Decay

B. P. HINCKS AND B. PONTECORVO
National Research Council of Canada, Chalk River Laboratory, Chalk River, Ontario, Canada
July 26, 1948

THE energy spectrum of the charged particles (commonly assumed to be electrons) emitted in the 2.2-μsec. meson decay is still unknown. Conversi and Piccioni in 1944 deduced from the relative numbers of decay electrons escaping from iron plates 0.5 cm and 5 cm

2) that less than 0.03 count per hour can be due to radiation from 25-Mev electrons in our arrangement. Consequently, it may be seen from Table I that at least a substantial fraction of the electrons must have a range greater than 15 g/cm² of carbon. Therefore, we conclude that there are decay electrons having energies greater than 25 Mev and therefore that the 2-particle decay process (Eq. (1)), with a *unique* energy of about 25 Mev for the decay electron, is incompatible with our results.

We observe, however, that a *maximum* energy of about 50 Mev for the decay electrons would be consistent with the data of Table I.

On the Range of the Electrons in Meson Decay

J. STEINBERGER
The Institute for Nuclear Study, University of Chicago, Chicago, Illinois
(Received January 10, 1949)

An experiment has been carried out by the University of Chicago and on Mt. Evans, Colorado, to determine the absorption of the electrons emitted in the decay of cosmic-ray mesons. Approximately 8000 counts have been obtained, using a hydrocarbon as the absorbing material. These data are used to deduce some features of the energy spectrum of the decay electrons. The resolution of the apparatus is calculated, taking the geometry, scattering, and radiation into account. The results indicate that the spectrum is either continuous, from 0 to about 55 Mev with an average energy ~32 Mev or consists of three or more discrete energies. No variation of the lifetime with the thickness of the absorber is observed. The experiment, therefore, offers some evidence in favor of the hypothesis that the μ-meson disintegrates into 3 light particles.
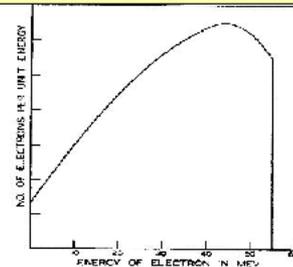
Fig. 9. The decay electron spectrum in this figure has been calculated to give as good a fit as possible with the data, at the same time excluding energies greater than 55 Mev. The limits of error of this spectrum are unknown, but large.
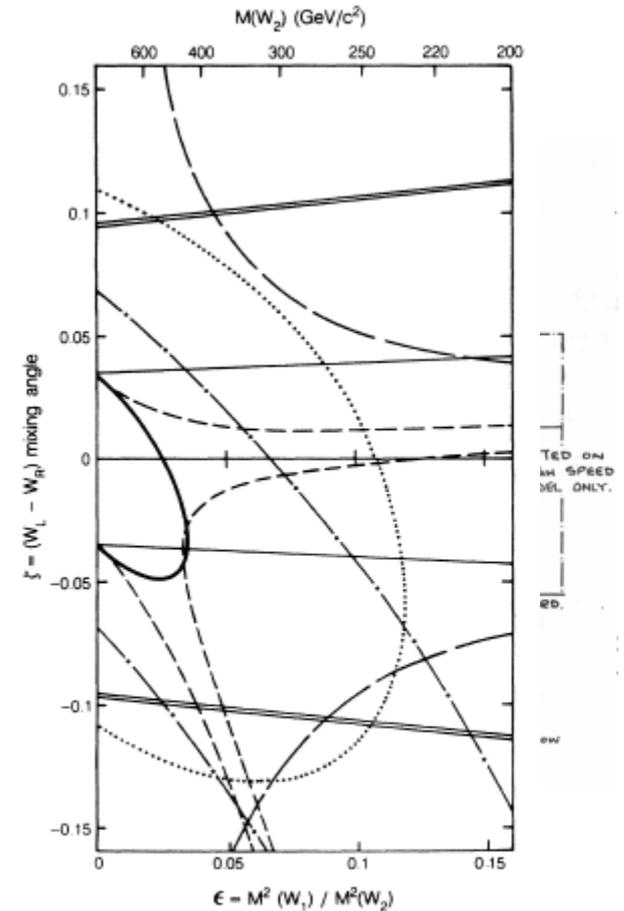
Muon decay parameters

•

FIG. 1. Experimental 90% confidence limits on the mass squared ratio ϵ and mixing angle ζ for the gauge bosons W_1 and W_2. The allowed regions are those which include $\epsilon = \zeta = 0$. The bold ellipse is the combined result from the analysis presented in this paper and from our μSR analysis (Refs. 11 and 12). The sources of the other limits are described in the text.
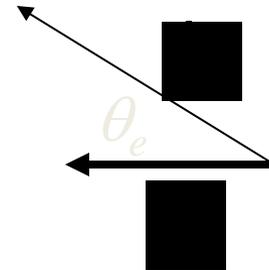
e^+ spectrum in $x, \cos\theta_e$

$$rate \sim x^2 \left[3 - 3x + \frac{2}{3}\rho(4x-3) + 3\eta x_o \left(\frac{1-x}{x}\right) + P_\mu \xi \cos\theta_e \left(1 - x + \frac{2}{3}\delta(4x-3)\right) \right]$$

Spectral shape in $x, \cos\theta_e$ is characterized in terms of four parameters -- ρ, η, ξ, δ

P_μ is the muon polarization

$$E_e^{max} \equiv \frac{m_\mu^2 + m_e^2}{2m_\mu} \qquad x_o \equiv \frac{m_e}{E_e^{max}} \qquad \boxed{x \equiv \frac{E_e}{E_e^{max}}}$$

(L. Michel, A. Sirlin)

Muon decay parameters in terms of Non SM weak couplings

$$\rho = \frac{3}{4} - \frac{3}{4}[|g_{RL}^V|^2 + |g_{LR}^V|^2 + 2|g_{RL}^T|^2 + 2|g_{LR}^T|^2$$

$$+ Re\,(g_{RL}^S g_{RL}^{T*} + g_{LR}^S g_{LR}^{T*})],$$

$$\eta = \frac{1}{2}Re[g_{RR}^V g_{LL}^{S*} + g_{LL}^V g_{RR}^{S*} + g_{RL}^V(g_{LR}^{S*} + 6g_{LR}^{T*}) + g_{LR}^V(g_{RL}^{S*} + 6g_{RL}^{T*})],$$
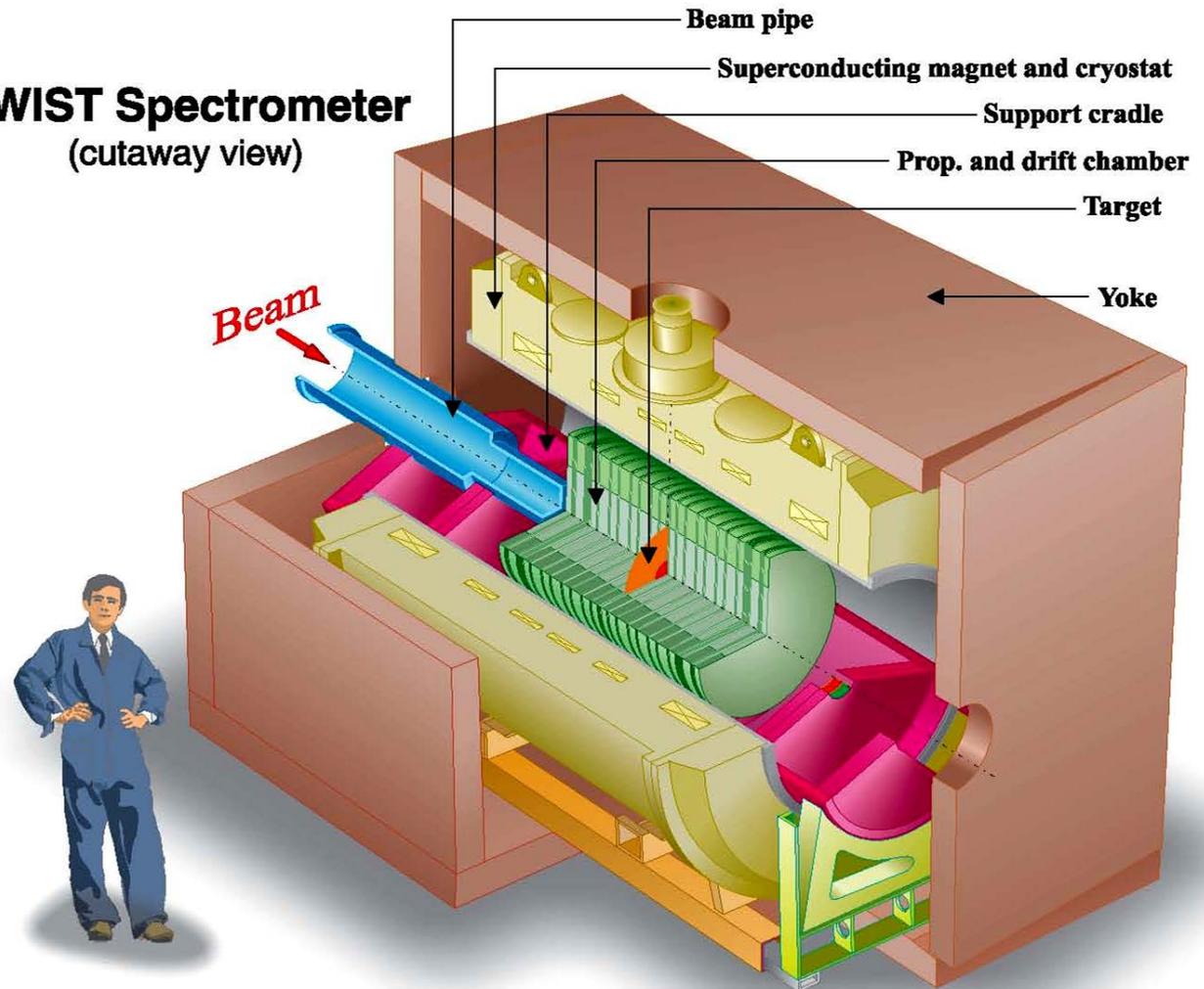
$$\xi = 1 - \frac{1}{2}|g_{LR}^S|^2 - \frac{1}{2}|g_{RR}^S|^2 - 4|g_{RL}^V|^2 + 2|g_{LR}^V|^2 - 2|g_{RR}^V|^2$$

$$+ 2|g_{LR}^T|^2 - 8|g_{RL}^T|^2 + 4Re(g_{LR}^S g_{LR}^{T*} - g_{RL}^S g_{RL}^{T*}),$$

$$\xi\delta = \frac{3}{4} - \frac{3}{8}|g_{RR}^S|^2 - \frac{3}{8}|g_{LR}^S|^2 - \frac{3}{2}|g_{RR}^V|^2 - \frac{3}{4}|g_{RL}^V|^2 - \frac{3}{4}|g_{LR}^V|^2$$

$$- \frac{3}{2}|g_{RL}^T|^2 - 3|g_{LR}^T|^2 + \frac{3}{4}Re(g_{LR}^S g_{LR}^{T*} - g_{RL}^S g_{RL}^{T*}).$$

The **TWIST** Spectrometer

- Use highly polarized μ^+ beam.

- Stop them in a very symmetric detector.

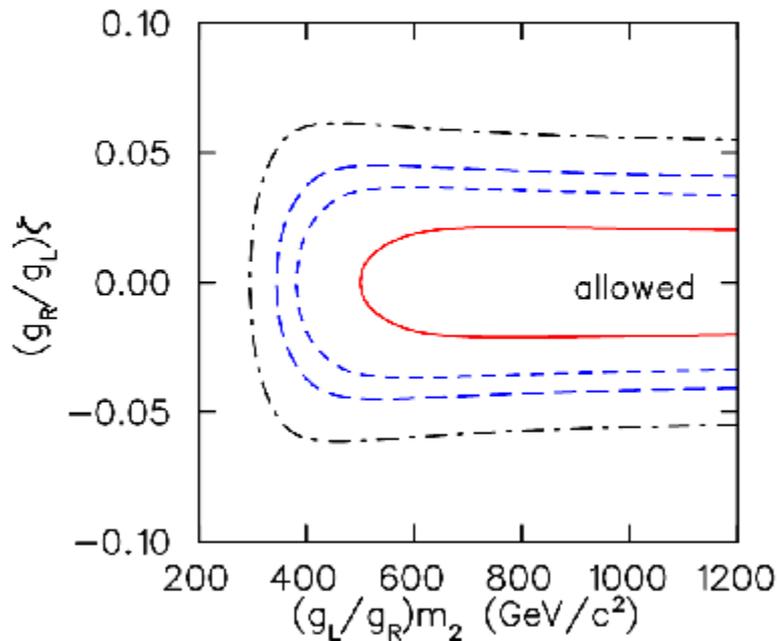- Decay e^+ are tracked through uniform, well-known field.

TWIST Spectrometer
(cutaway view)

Beam

Beam pipe

Superconducting magnet and cryostat

Support cradle

Prop. and drift chamber

Target

Yoke

Final **TWIST** results

- $\rho = 0.74991 \pm 0.00009$ (stat) ± 0.00028 (syst)

- $\delta = 0.75072 \pm 0.00016$ (stat) ± 0.00029 (syst)

- $P_\mu \xi = 1.00084 \pm 0.00035$ (stat) $\begin{array}{l} + 0.00165 \\ - 0.00063 \end{array}$ (syst)
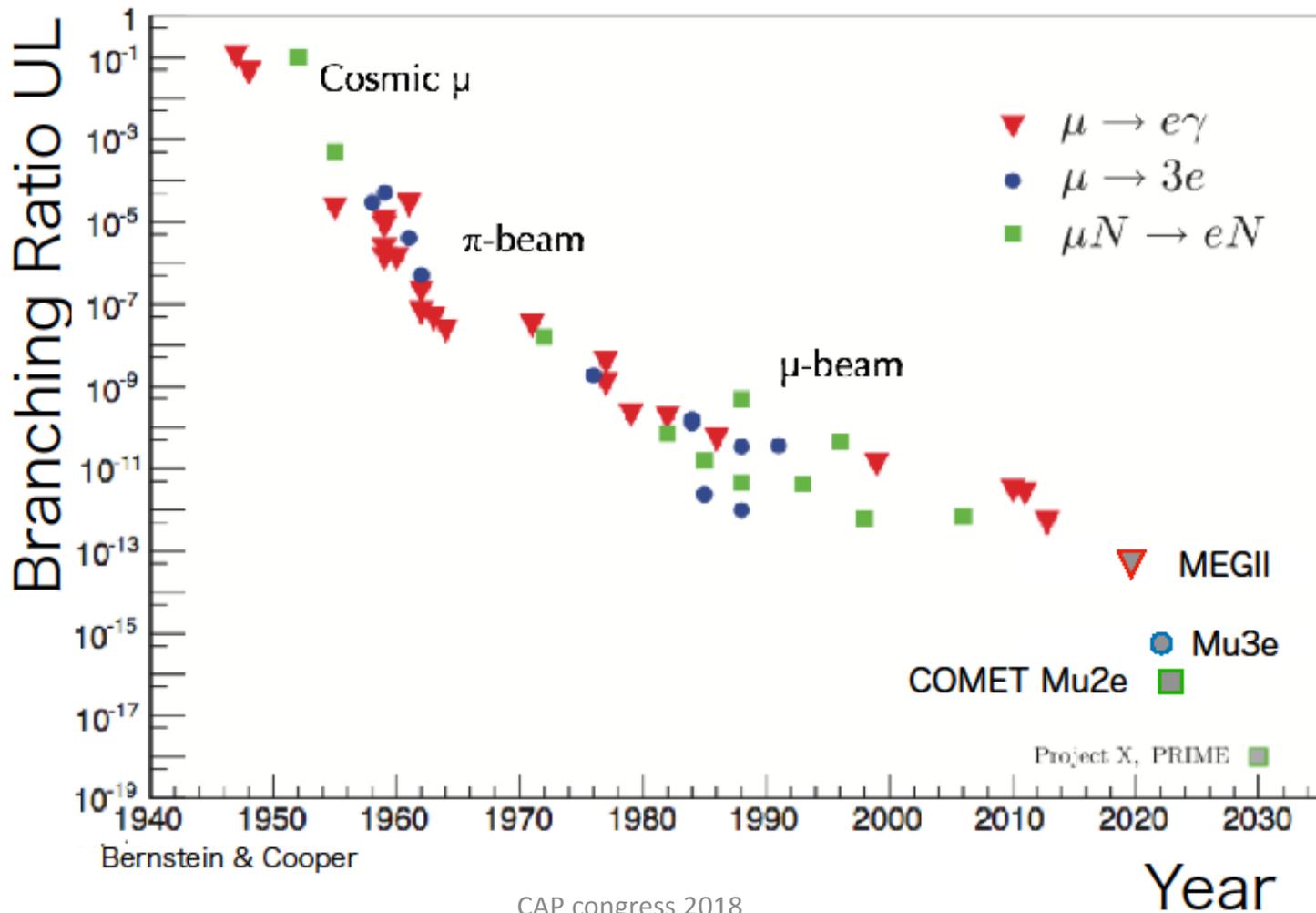
$\mathcal{TWIST}$ impact on Left-Right model

New limits on non-manifest (generalised) left-right symmetric models.

Legend:
- —— **This measurement (for $\mathcal{P}_\mu \xi = 1$)** (red solid)
- - - - - Recent TWIST ρ, δ (blue dotted)
- - - - Previous TWIST $\mathcal{P}_\mu \xi$ (blue dashed)
- -·- Pre-TWIST (black dash-dot)

Rare decay of the muon

The Zurich meeting (1977)

Steven Weinberg

Harvard University, Cambridge, Massachusetts

Abstract

A review is presented of the general principles and recent developments in unified gauge theories of the weak, electromagnetic, and strong interactions.

Muon nonconservation is also possible in the standard model, if there is more than one scalar doublet. The coupling of Higgs bosons to any particle are generally proportional to the mass of that particle, so one-loop diagrams in which Higgs bosons are emitted and reabsorbed from lepton lines give very small contributions. The dominant effect comes from two-loop diagrams, in which a Higgs boson is emitted from a lepton and absorbed by a virtual W or Z. The branching ratio here depends on many unknown parameters, but under the most favorable circumstances it could take values[41] as large as $(\alpha/\pi)^3 \sim 10^{-8}$.

Very recently, a new upper limit[42] of 3.6×10^{-9} has been set on the $\mu \to e\gamma$ branching ratio. From the perspective of $SU(2) \times U(1)$ gauge theories, this is almost but not quite stringent enough to shed light on the question of whether muon conservation is really a fundamental symmetry principle. An improvement of one more order of

magnitude in the sensitivity of this experiment (and experiments on $\mu\mathcal{N} \to e\mathcal{N}$) would be very illuminating.
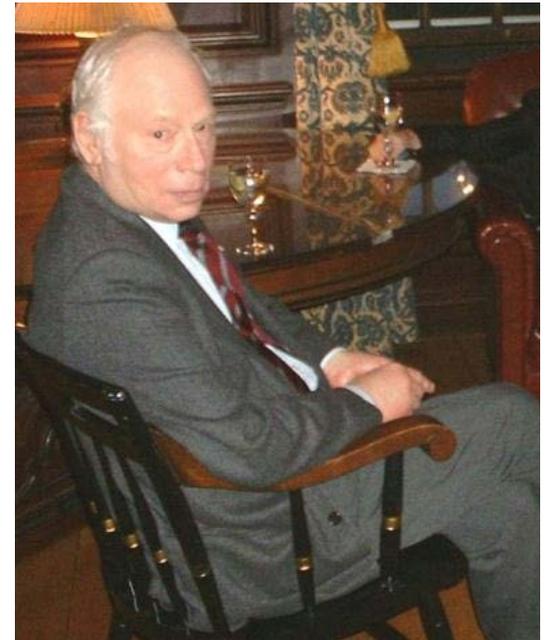
42) P. Depommier *et al.*, (Montréal-UBC-Triumf collaboration) to be published. Also see the report of H. P. Povel (ETH-Zürich-SIN-Munich collaboration) at this conference.[See also the edit. postscript after L. Wolfenstein's report.

43) M. Kobayashi and K. Maskawa, Prog. Theor. Phys. 49, (1973) 652; A. Pais and J. Primack, Phys. Rev. D8, (1973) 3063; L. Maiani, Phys. Lett. 68B, (1976) 183; S. Pakvasa and H. Sugawara, Phys. Rev. D14, (1976) 305.

44) T. D. Lee, Phys. Rev. D8, (1973) 1226 and Phys. Rep. 9C, (1974) 143; S. Weinberg, Phys. Rev. Lett. 37, (1976) 657.

The Zurich meeting

WEAK INTERACTIONS – *Workshop P*

L. Wolfenstein

Carnegie-Mellon University, Pittsburgh, Pennsylvania 15213, USA

Abstract

The study of the weak interactions involving pions, muons, and nuclei can clarify the laws of weak interactions. The present theoretical interest in muon-electron universality, nonconservation of muon number, and second-class currents is discussed.

This session is devoted to weak interaction processes involving pions, muons, and nuclei. The emphasis will be on the role of these processes in clarifying the form of the weak interaction Hamiltonian. The theory of weak interactions has had exciting developments in the last few years. A particular form of unified gauge theory of weak and electromagnetic interactions, which we will refer to as the standard model,[1] has had two striking successes: (1) neutral weak currents have been discovered in high-energy neutrino interactions with protons and neutrons and these currents appear to have a strength and form consistent with the predictions of the model. (2) Charmed particles, needed in the model to explain the absence of strangeness-changing neutral currents, have been discovered with the expected decay modes. Nevertheless, there are indications that this model may not be the total story.

If there is a conclusion to this talk, it is that the fundamental laws of weak interactions must be explored in many different ways: beta-decay, weak processes of pions and muons, atomic physics, colliding e^+e^- beams, and high-energy neutrino beams at the largest accelerators all have a role to play.

Editorial postscript:

As this contribution was prepared before the conference it does not contain the latest experimental results on muon number violating processes. With the permission of the authors we are quoting the following preliminary results which have been presented in the workshop P on weak interactions.

The ratio of $\mu \rightarrow e\gamma$ relative to the dominant decay mode is

$$R_{\mu e\gamma} < 3.6 \times 10^{-9}$$

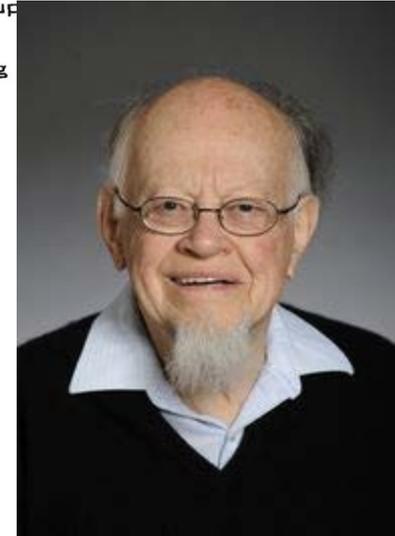reported by J.M. Poutissou from the TRIUMF group (abstract P4) and

$$R_{\mu e\gamma} < 1.6 \times 10^{-9} \quad (90\% \text{ CFL})$$

reported by H.P. Povel from the SIN group (abstract P18).

B. Hahn from the Bern group working SIN reported the following preliminary limits on μe conversion on ^{32}S:

$$R_{\mu^- e^-} < 4 \times 10^{-10}$$

and $R_{\mu^- e^+} < 1 \times 10^{-9}$.

6/12/2018   CAP congress 2018

MUeGAMMA

TRIUMF	SIN/PSI	LAMPF
1977 Less than 10^{-9}	1977 less than 10^{-9}	
		2002 Less than $1.2 \cdot 10^{-11}$
	2010 less than $4.2 \cdot 10^{-13}$	

Mu to E

Process	upper limit	place	year	reference
$\mu^- + Cu \rightarrow e^- + Cu$	$< 1.6 \times 10^{-8}$	SREL	1972	[67]
$\mu^- + {}^{32}S \rightarrow e^- + {}^{32}S$	$< 7 \times 10^{-11}$	SIN	1982	[68]
$\mu^- + Ti \rightarrow e^- + Ti$	$< 1.6 \times 10^{-11}$	TRIUMF	1985	[69]
$\mu^- + Ti \rightarrow e^- + Ti$	$< 4.6 \times 10^{-12}$	TRIUMF	1988	[70]
$\mu^- + Pb \rightarrow e^- + Pb$	$< 4.9 \times 10^{-10}$	TRIUMF	1988	[70]
$\mu^- + Ti \rightarrow e^- + Ti$	$< 4.3 \times 10^{-12}$	PSI	1993	[71]
$\mu^- + Pb \rightarrow e^- + Pb$	$< 4.6 \times 10^{-11}$	PSI	1996	[72]
$\mu^- + Ti \rightarrow e^- + Ti$	$< 6.1 \times 10^{-13}$	PSI	1998*	[23]
$\mu^- + Au \rightarrow e^- + Au$	$< 7 \times 10^{-13}$	PSI	2006	[1]

Reach of rare Muon decay

CHAPTER 2. PHYSICS MOTIVATION 28

Figure 2.9: Relation between $\mu^+ \to e^+\gamma$ and $\mu^- - e^-$ conversion estimated from Eq.(2.15). The parameter κ interpolates between the photonic and the non-photonic contributions. The current searches are sensitive to $O(10^3)$ TeV energy scale. The anticipated COMET Phase-I limits are shown.

Mu to E conversion
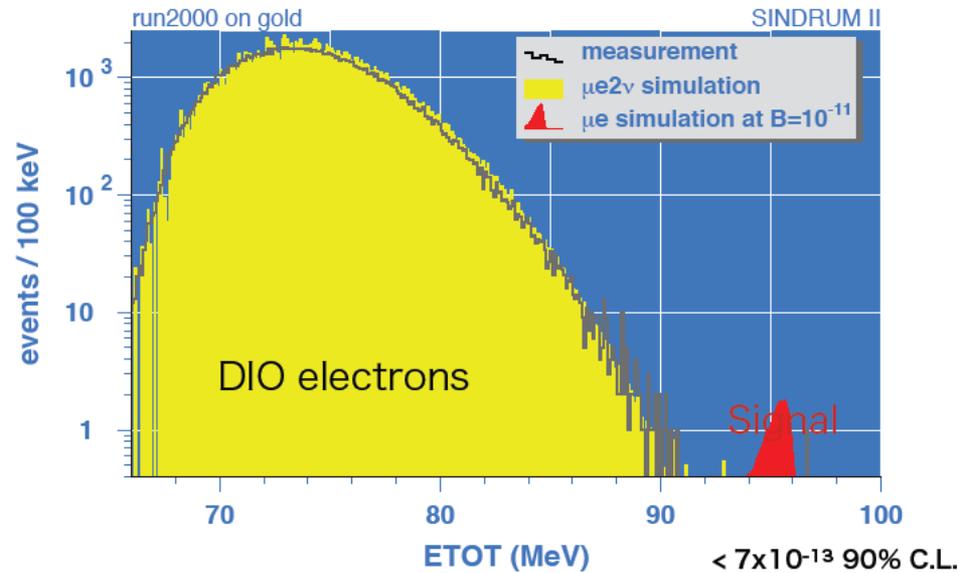
R.M.Dzhilkibaev, V.M.Lobashev
INR 1989 proposal
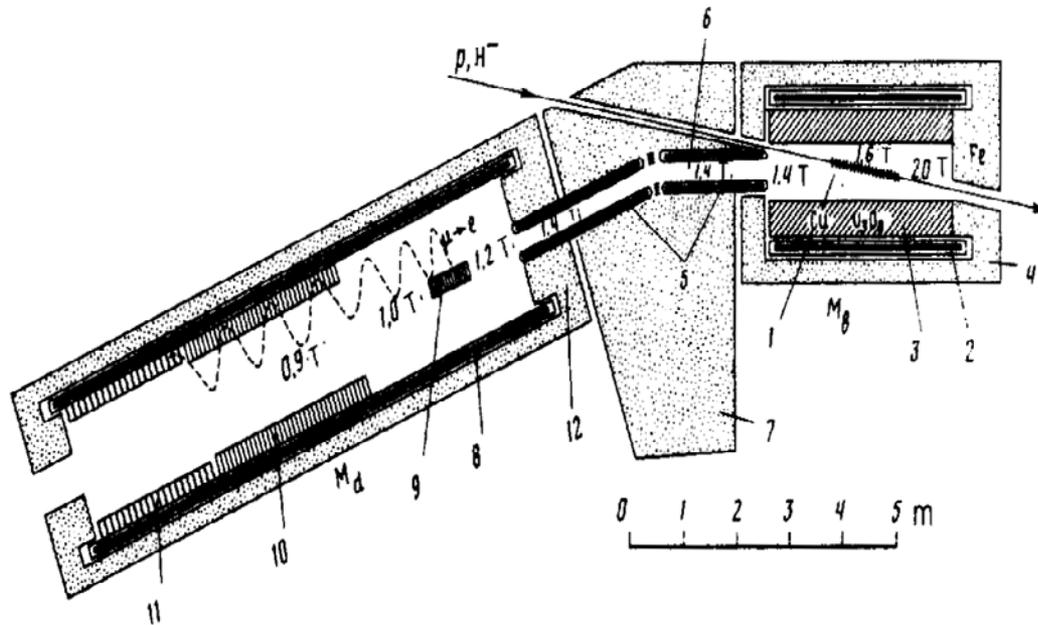
FIG. 1. Diagram of the apparatus: 1—meson-producing target (tungsten); 2—superconducting solenoid; 3—solenoid shield; 4—steel magnet yoke; 5—collimator solenoids; 6—collimator; 7—shielding (heavy iron); 8—detecting-system solenoid; 9—targets for stopping of muons; 10—detector (proportional chambers); 11—total-absorption scintillation spectrometer; 12—magnet yoke.

Fermilab MU2E

Meet Mu2e magnets

Production Solenoid (PS)

Detector Solenoid (DS)

2.0 T

-4.6 T

2.5 T

1.0 T

Transport Solenoid (TS)

Detector Region: Uniform Field 1T
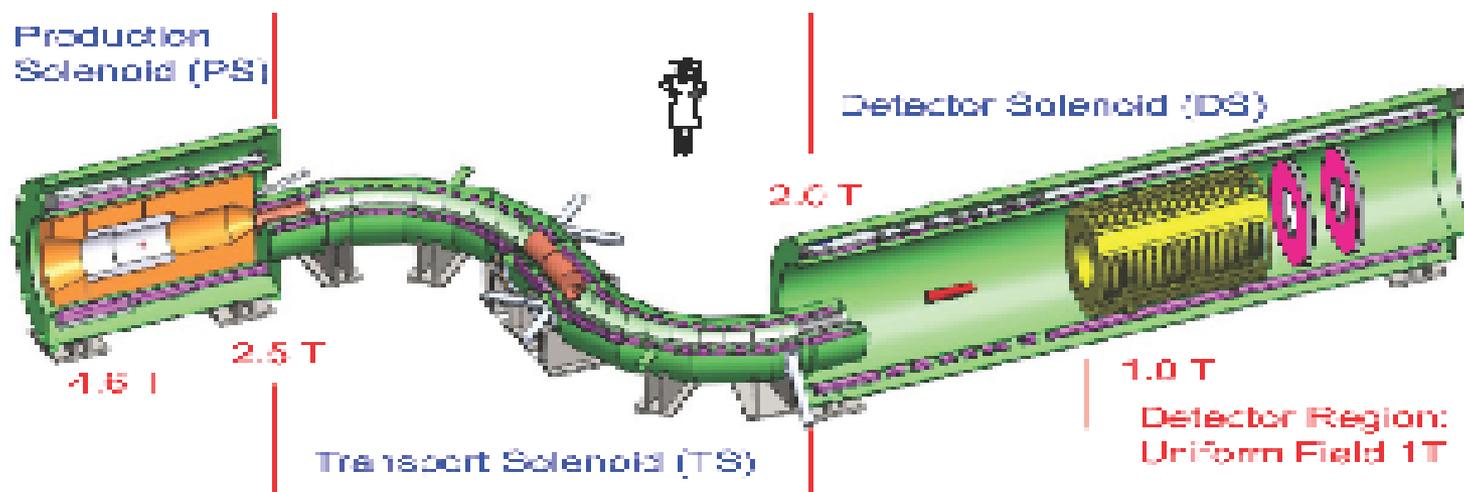
Graded B for most of length

Not shown: Cosmic Ray Veto, Extinction Monitor

Andrei Gaponenko   33   IF Seminar 2013-12-12

COMET at J-PARC

COMET Phase I & II

- Phase I

  - Beam background study, achieve an intermediate sensitivity of $< 10^{-14}$

  - 8GeV, 3.2kW, 150 days of DAQ

- Phase II

  - 8GeV, 56kW, 1 year DAQ to achieve the COMET final goal of $< 10^{-16}$ sensitivity
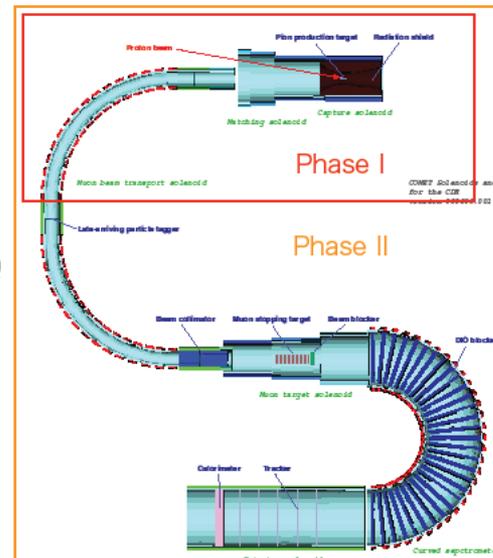
Rare decay of the muon
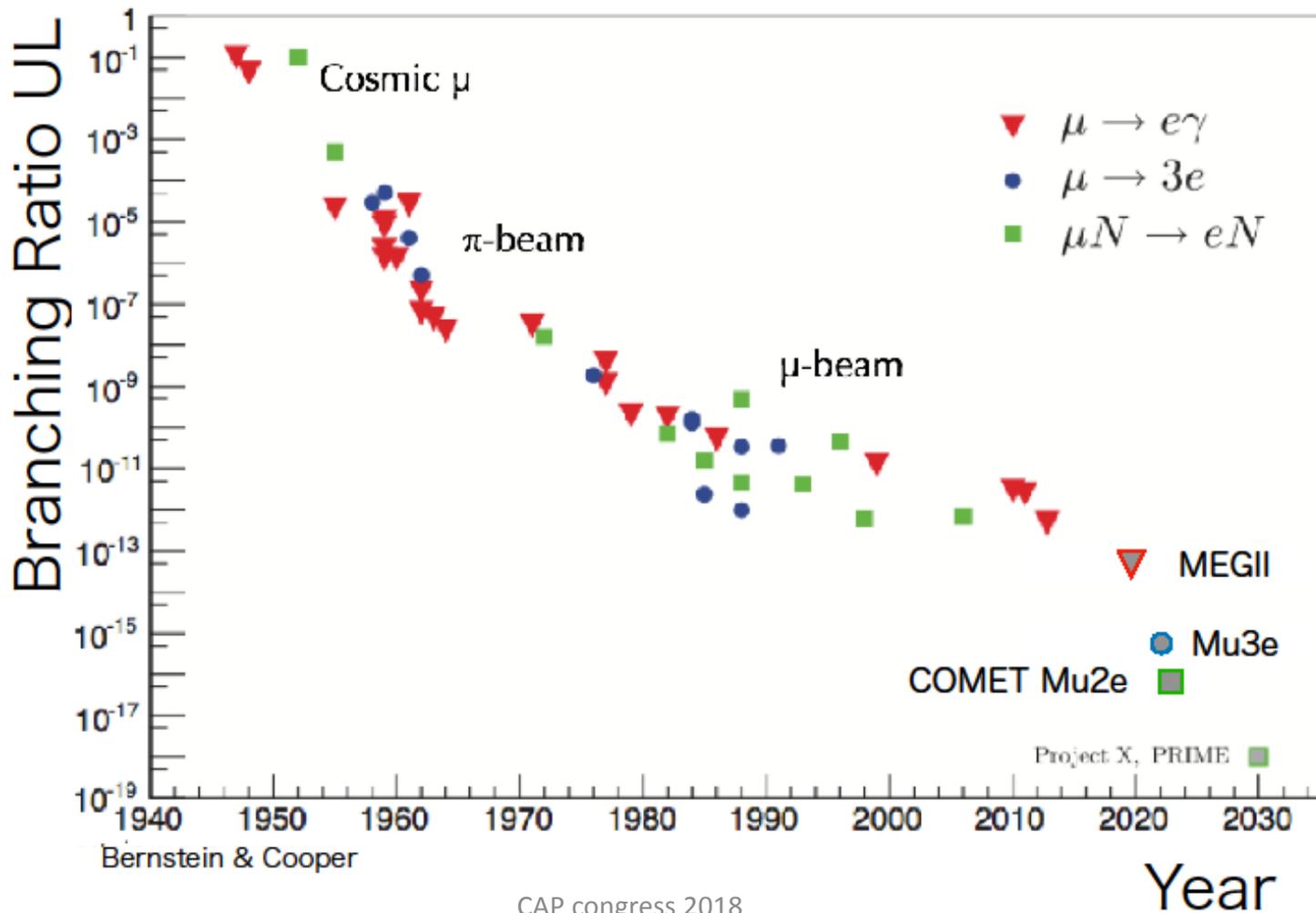
ELEMENTARY PARTICLES
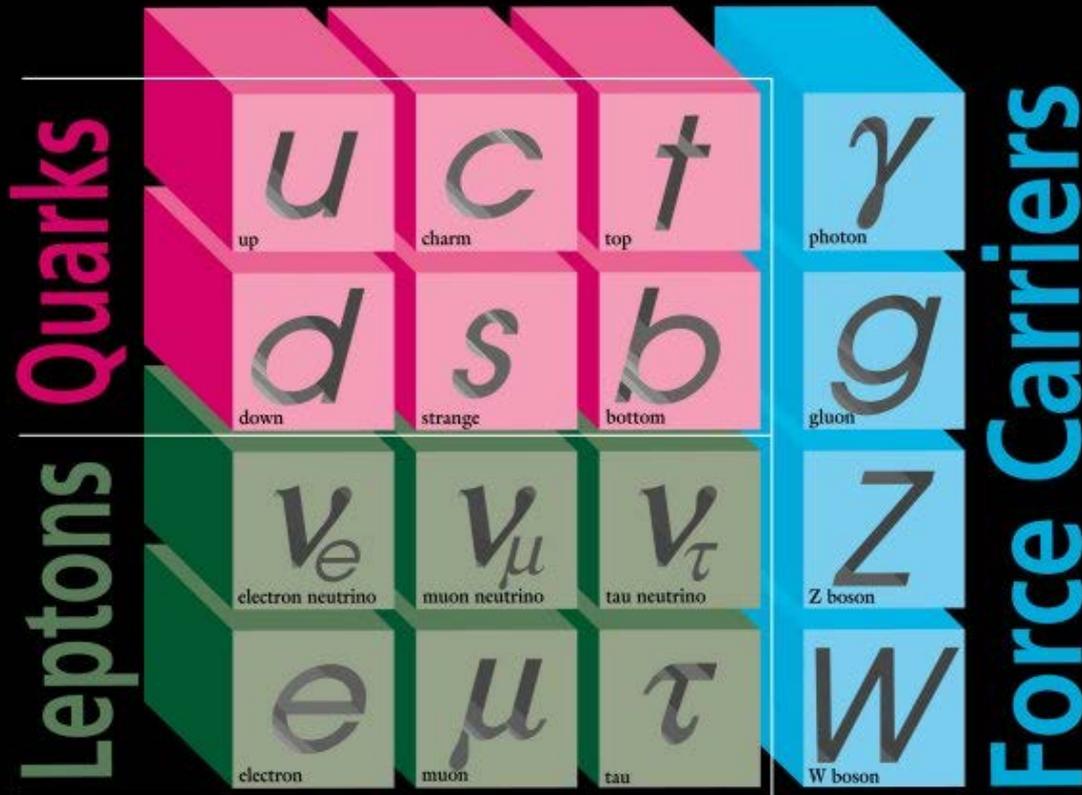
Three Generations of Matter

History of neutrino

- Postulated in 1930 by W.Pauli to explain some anomalous decay properties of nuclei.
  - (Pauli will get the Nobel prize in 1945 but not for this!!)
- Fermi builds his theory of Beta decay upon the neutrino hypothesis (1933)
  - Fermi will get a Nobel prize in 1938 but not for this!!

- Pontecorvo now in Canada proposed a method to detect neutrino(1945)
- Neutrino mass first limit: Pontecorvo/Hanna 1948
- First neutrino "seen" in experiment in 1956 (Reines, Nobel prize 1995)
- Neutrino predicted to be left handed in 1957 by Landau ,T.D.Lee,C.Yang,A.Salam.
  - Lee & Yang Nobel prize (1957),Salam (1979)
- Muon neutrino Left handedness confirmed experimentally (1962) (Steinberger Lederman, Schwarz, Nobel prize1982)

Neutrino Oscillations

- Neutrino oscillation predicted by B. Pontecorvo 1957 if neutrino have a finite mass: This was bold prediction at the time

- Neutrino oscillation confirmed 1998 in SuperKamiokande Japan.
  - (M.Koshiba/R.Davis) Nobel prize 2002.
- Solar neutrino oscillation confirmed by the SNO experiment in Canada (2002) A.McDonald(Queen's) Pontecorvo prize awarded to the team and Nobel prize 2015, Breakthrough prize 2016

- Neutrino oscillation confirmed for accelerator made neutrino and for reactor made antineutrino.(K2K and KAMLAND experiments in Japan 2004)
.
- First detection of neutrinos from the earth (Kamland, Japan 2005)

- First evidence for Theta13 from T2K (June 2011)

A quote

All main ideas of the modern neutrino physics were suggested by Bruno Pontecorvo.

Val Telegdi

Herb Chen's idea

- *Chen, Herbert H. (September 1984). "Direct Approach to Resolve the Solar-Neutrino Problem". Physical Review Letters. **55** (14): 1534–1536.*

- *SNO was based on his idea to use heavy water as a detector mass.*

Summer/Coop students at TRIUMF

DESIGN OF A NEUTRINO BEAM FOR A LONG BASELINE
NEUTRINO OSCILLATION EXPERIMENT

by
JARED ANDERSON

TRIUMF
4004 WESBROOK MALL
VANCOUVER, BC

Physics Co-op Work Term Report
in partial fulfillment
of the requirements of the Physics Co-op Program
Summer 1993

Jared Anderson
Department of Physics and Astronomy
University of Victoria

T2K Collaboration

~ 400 members from 12 Countries

Japan, US, Canada, France, UK, Switzerland, Poland, Korea, Russia, Spain, Italy, Germany

Tokai-to-Kamioka (T2K) long baseline neutrino oscillation experiment
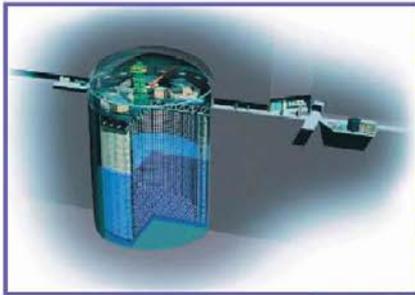
Super-Kamiokande
(ICRR, Univ. Tokyo)

295km

J-PARC Main Ring
(KEK-JAEA, Tokai)

ν_e appearance (θ_{13})

CP phase δ (degrees)

$\Delta m^2_{13} = 2.5 \times 10^{-3}$ eV^2
$\Delta m^2_{13} = 1.9 \times 10^{-3}$ eV^2
$\Delta m^2_{13} = 3.0 \times 10^{-3}$ eV^2

$\sin^2 2\theta_{23} = 1$
$\Delta m^2_{12} = 8.2 \times 10^{-5}$ eV^2
$\tan^2 \theta_{12} = 0.4$

> x10

CHOOZ excluded

$\sin^2 2\theta_{13}$
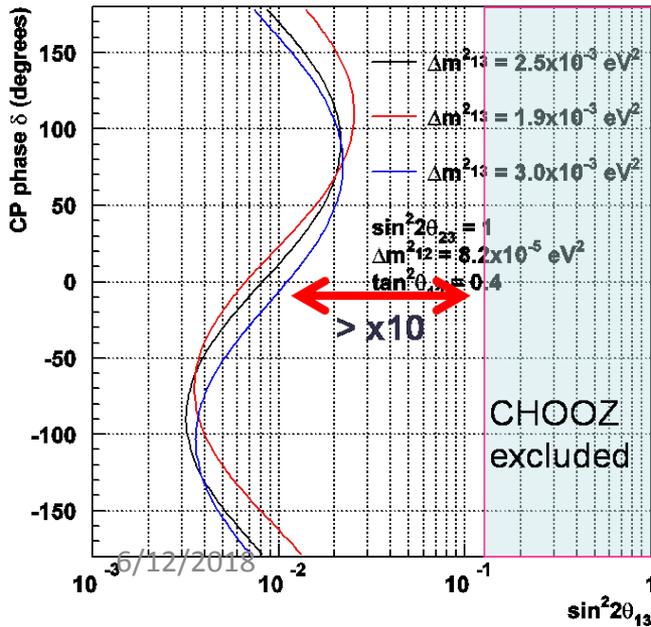
- Intense sub GeV ν_μ beam from J-PARC
  - Off-axis narrow band beam tuned at osc. max
  - Construction 2004~2008
- World largest Super-Kamiokande at 295km
- Main goals
  - w/ 750kWx5yr(15000hr) (approved)
  - Discovery of ν_e appearance (2011)
  - Precise measurements on ν_μ disapp.

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振動確率 @
$\Delta m^2 = 3 \times 10^{-3}$ eV^2

$\nu_\mu \Phi \times \sigma$ au

OA0°
OA2°
OA2.5°
OA3°

GeV

1600ν_μCC/yr/22.5kt
(2.5deg)

29
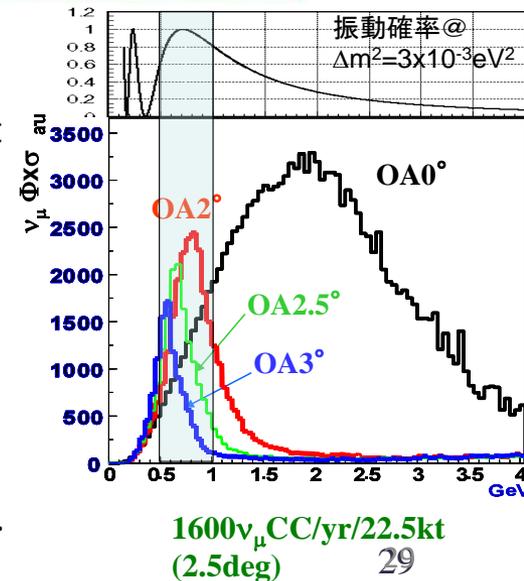
2018 status

Current neutrino picture

$$
\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}
$$

flavour · atmospheric · accelerator/reactor · solar · mass

where $c_{ij}=cos\theta_{ij}$, $s_{ij}=sin\theta_{ij}$
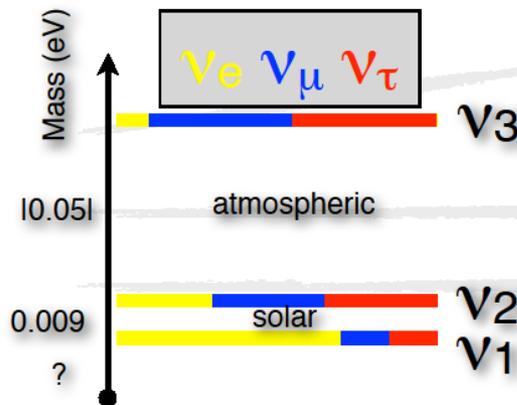
- What is the value of δ_{CP}??
- What is the mass hierarchy?
- Is PMNS parametrisation correct?
- What is the absolute mass scale?
- Why so small??
- What is the nature of neutrino mass?
  - Dirac or Majorana?

Mass (eV)

ν_e ν_μ ν_τ

ν_3

|0.05| atmospheric

ν_2

0.009 solar

ν_1

?

Imperial College London

J-PARC IAC 2018 03 05

Morgan O. Wascko
3

Theta13

World θ_{13} comparison

Ishitsuka@Moriond 2016 EW
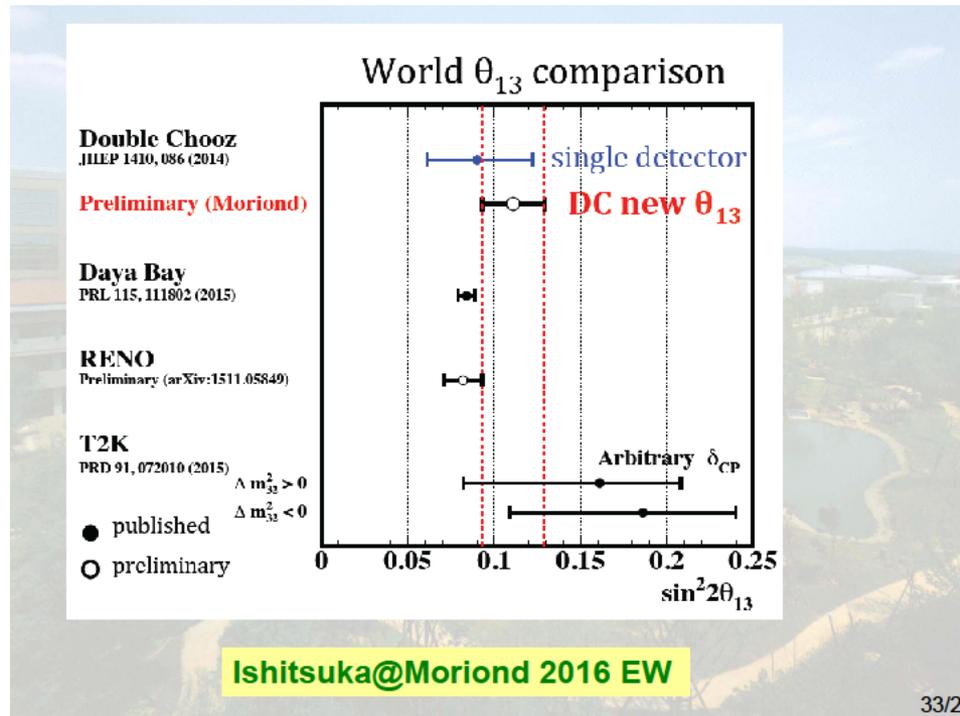
Another canadian idea (Konaka)

## E61 Experiment

- **Kiloton scale water Cherenkov detector** in J-PARC beam at ~1 km baseline

  - Make cross section measurements for T2K & Hyper-K

  - Same target material, thresholds, angular acceptance as far detector

- Detector can be moved to change off-axis angle: **Probe relationship between neutrino energy and observables**

- **Measure the electron (anti)neutrino cross section** and intrinsic backgrounds for CP violation search

- **Dope with Gd to measure neutron multiplicities** in neutrino interactions

- Requires % level detector calibration

- Now pursuing test experiment

  - Construction in 2019-2020, Operation starting in 2021

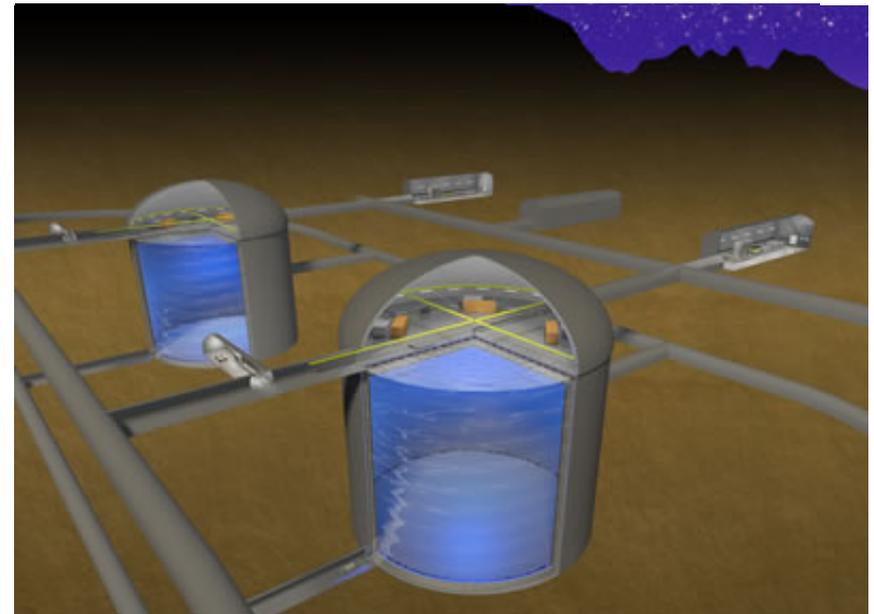 - Considering test beam lines at Fermilab and CERN

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J-PARC IAC 2018 03 05

Morgan O.
Wascko
23
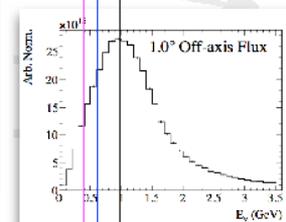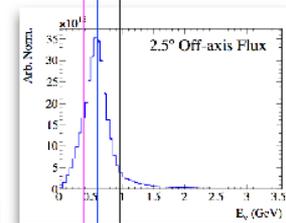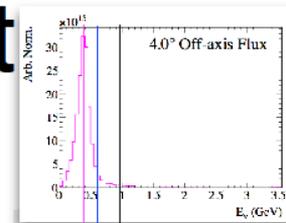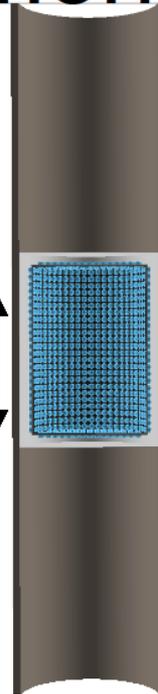
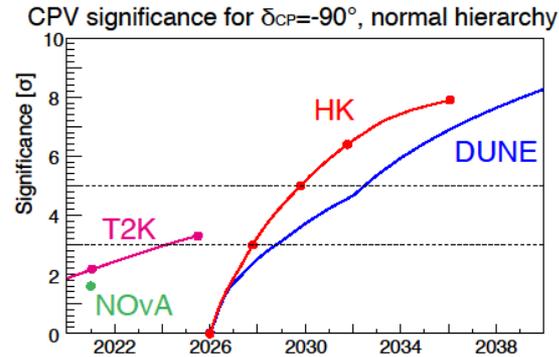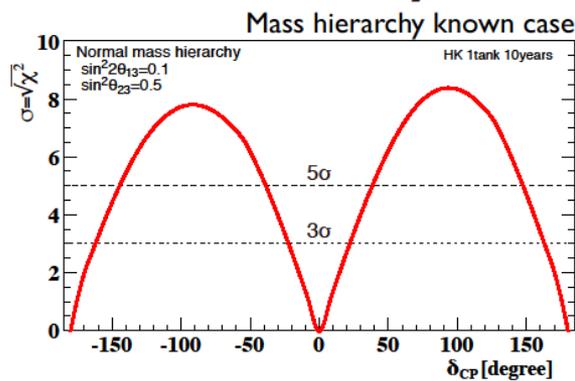# New long baseline experiments

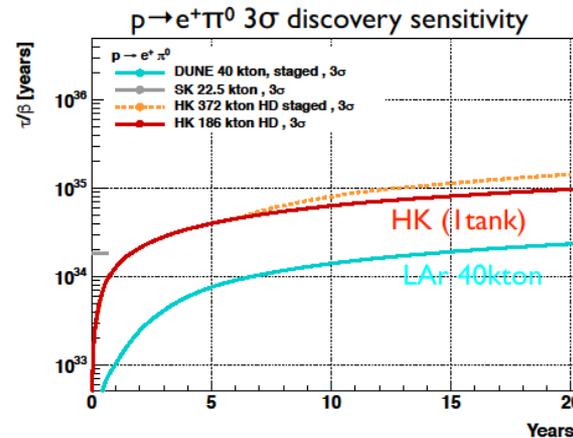**Fermilab project**
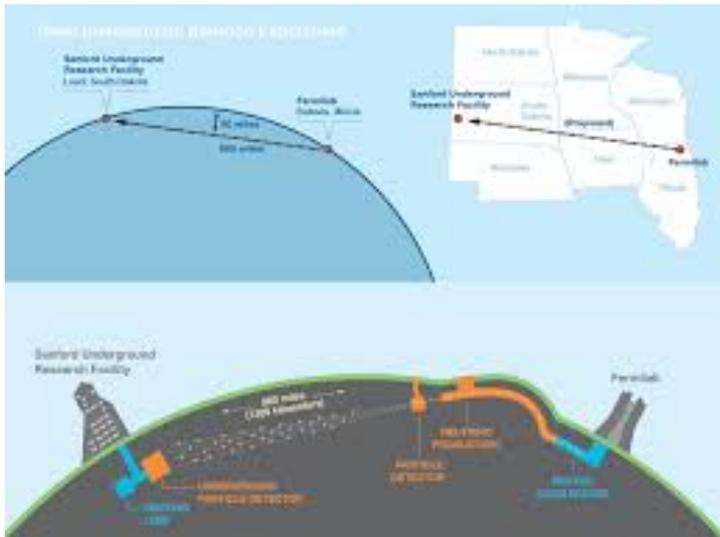
J-PARC/U of Tokyo

HK/Dune reach

Physics potential

- Definite discovery of CP violation in the lepton sector and measurement of CP asymmetry
  - Seamless program from T2K(-II)

- Proton decay discovery potential ~order of magnitude better than current limits
 - Reach 10^{35} years ($e^+\pi^0$)

Today's questions

- What is the mass of the three types of neutrinos
- Why are their masses so small (new physics)
- Are neutrino responsible for the matter- anti matter asymmetry of the universe (why do we exists at all?)
- What is the dark matter of the universe made of?
- Are there other "sterile" neutrino's (see recent neutrino conference results)
- Neutrinos as probe of stars
- Neutrinos in the universe and evolution in time

Murayama (Kavli/IPMU-Tokyo U)
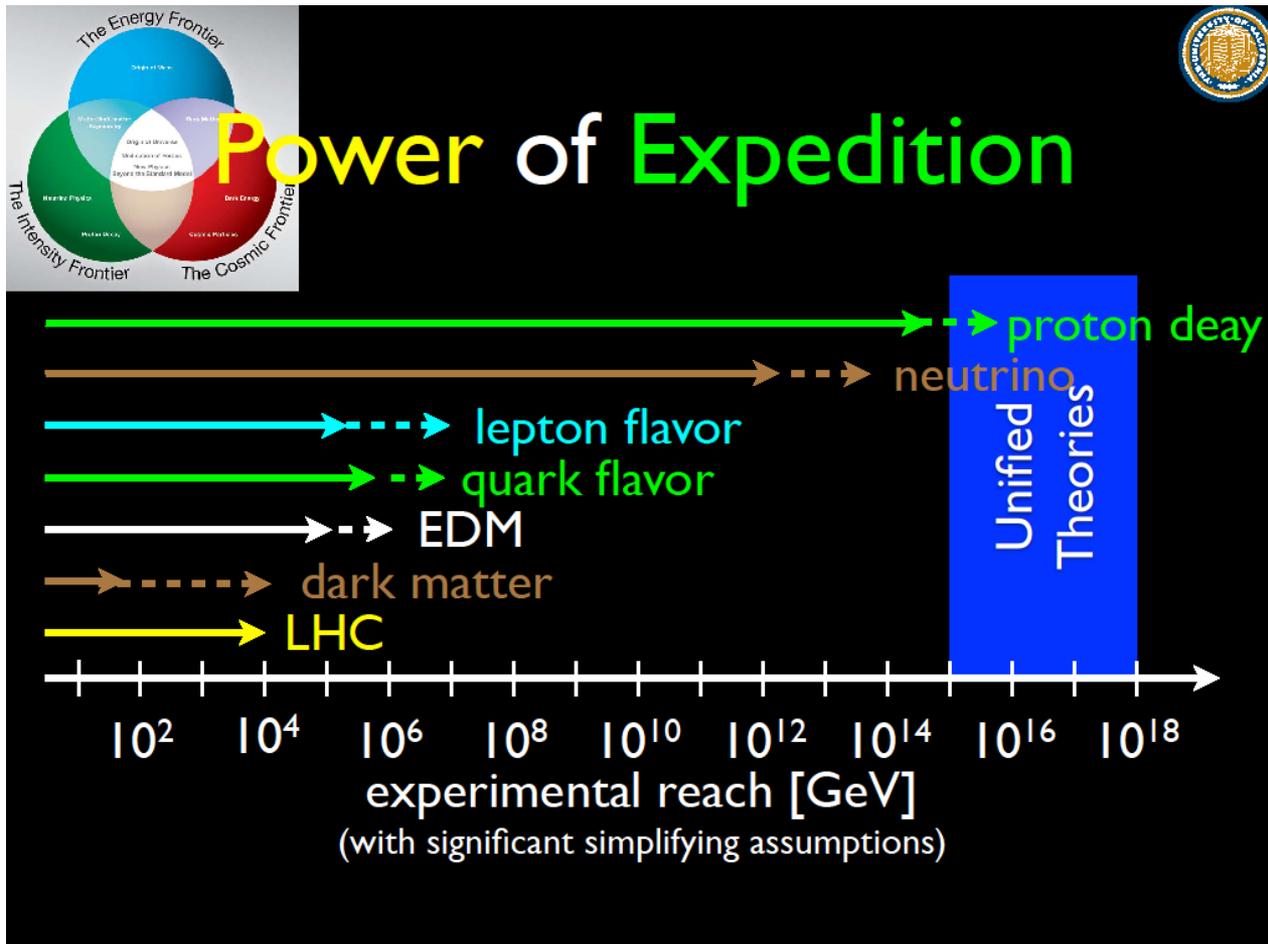
Leadership is not about driving the train but about laying down the tracks

Leadership is laying the tracks but many "drivers" are needed to go beyond the Standard Model

Conclusions

- LHC has given us the last missing piece of the Standard Model at the energy frontier, the Higgs boson.
- LHC has failed to reveal any anticipated new particle
  (for ex. SUSY)....so far.
- BSM physics can manifest itself in various observables to be studied at the intensity frontier.
- Canadian Particle Physicists with strong support from the Canadian tax payers through NSERC,CFI and NRC are at the fore front of the search for a more comprehensive "Standard Model " , the BSM (Best Standard Model)
- TRIUMF is well positioned to continue its strong participation in these many quests for the new Holy Grail.
- Thank you CAP for recognizing my contributions to this exciting field of research
- I would like to acknowledge that this was not done without a strong cooperation of my many colleagues, students, post docs and staff members……. This was always a team effort at TRIUMF
- It was in fact a family effort with Renee collecting the data of many of our experiments and my two sons sharing the hectic life style of a physicists ' home.

Merci!
Thank You!