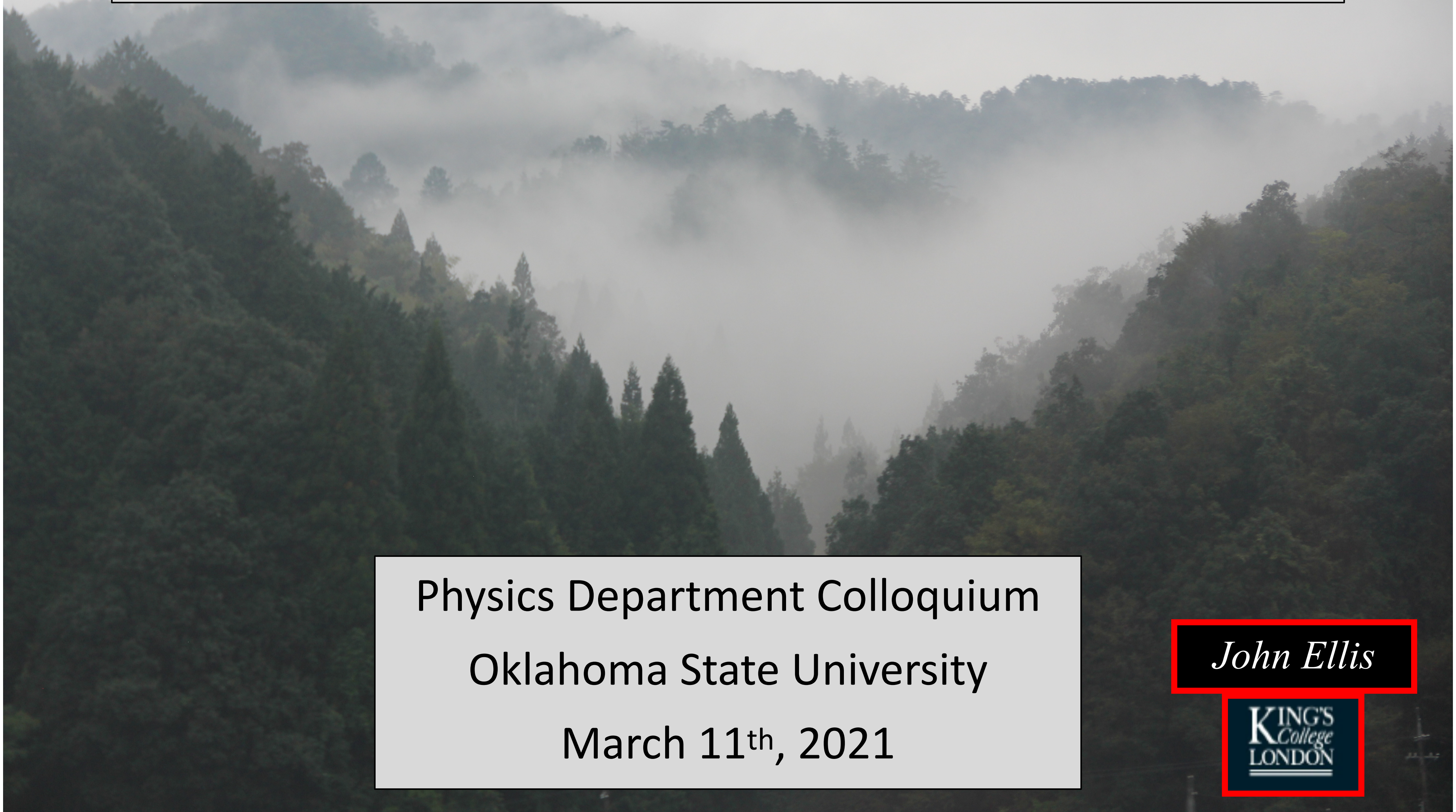
Grand Unified Theories & Proton Decay



Physics Department Colloquium

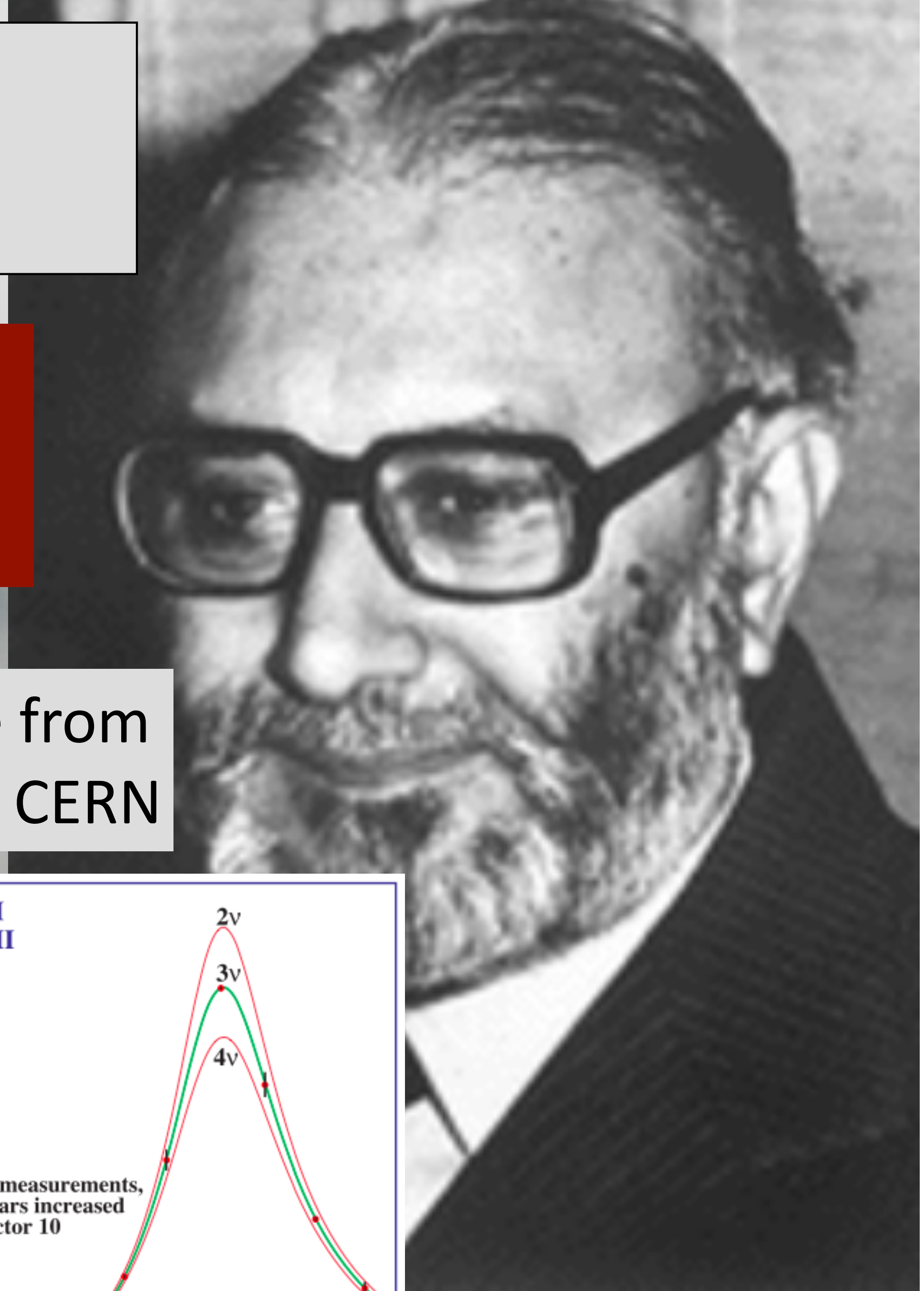
Oklahoma State University

March 11th, 2021

John Ellis

KING'S College LONDON

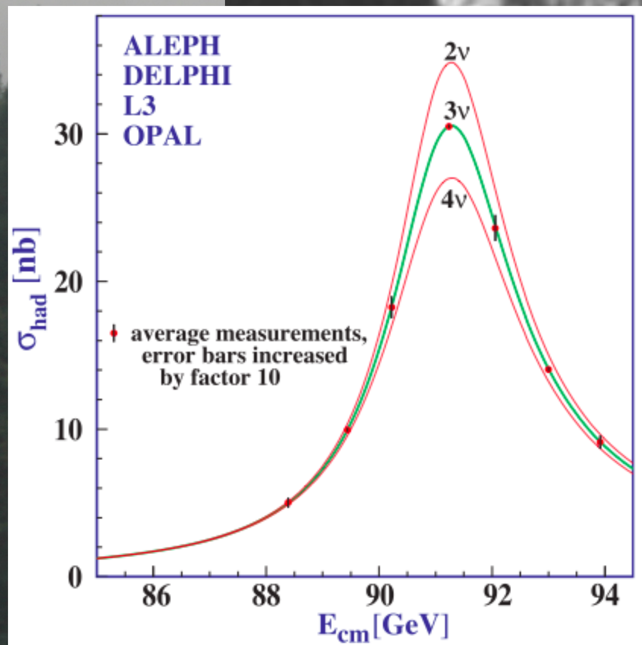
1967 The ‘Standard Model’ of Particle Physics



Abdus Salam,
Sheldon Glashow,
Steven Weinberg

1973

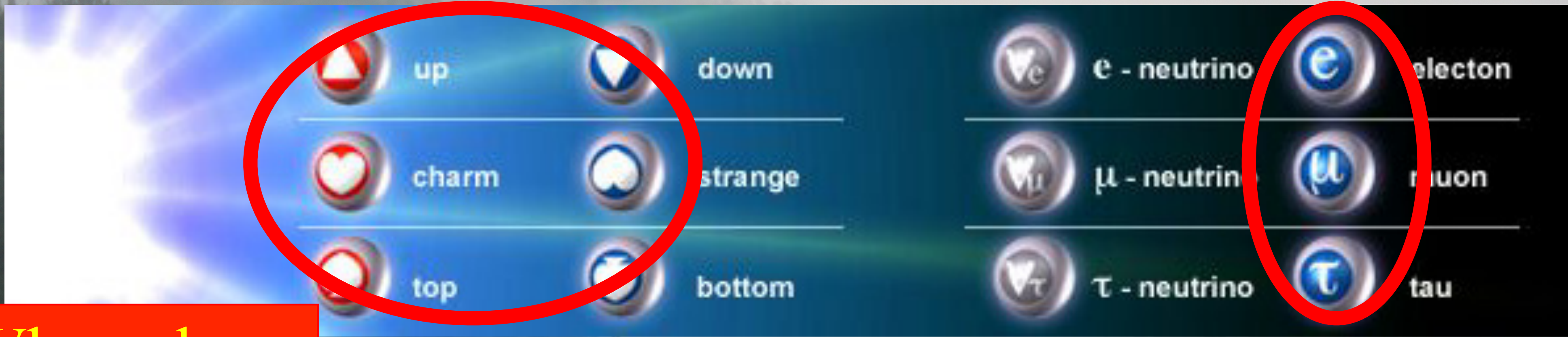
First evidence from experiment at CERN



Perfect agreement between theory and experiments in all laboratories

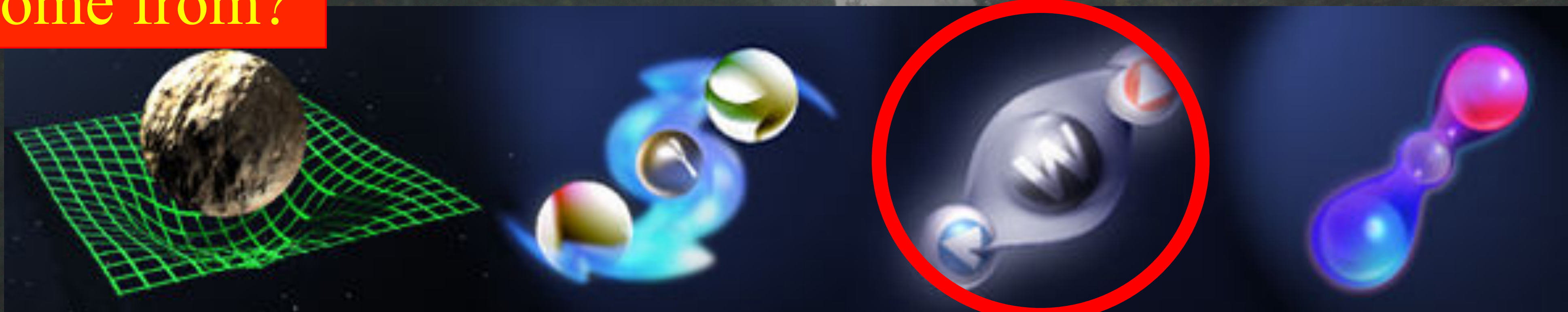
The ‘Standard Model’

The matter particles



Where does mass come from?

The fundamental interactions



Gravitation | electromagnetism | weak nuclear force | strong nuclear force

Structure of the Standard Model

- Particles and SU(3) × SU(2) × U(1) quantum numbers:

L_L E_R	$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L , \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L , \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L$ $e_R^- , \mu_R^- , \tau_R^-$	$(\mathbf{1},\mathbf{2},\text{-}1)$ $(\mathbf{1},\mathbf{1},\text{-}2)$
Q_L U_R D_R	$\begin{pmatrix} u \\ d \end{pmatrix}_L , \begin{pmatrix} c \\ s \end{pmatrix}_L , \begin{pmatrix} t \\ b \end{pmatrix}_L$ u_R , c_R , t_R d_R , s_R , b_R	$(\mathbf{3},\mathbf{2},+1/3)$ $(\mathbf{3},\mathbf{1},+4/3)$ $(\mathbf{3},\mathbf{1},\text{-}2/3)$

- Lagrangian:

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

gauge interactions

matter fermions

Yukawa interactions

Higgs potential

Tested < 0.1% before LHC

Testing now in progress

Parameters of the Standard Model

- Gauge sector:
  - 3 gauge couplings: g_3, g_2, g'
  - 1 strong CP-violating phase
- Yukawa interactions:
  - 3 charge-lepton masses
  - 6 quark masses
  - 4 CKM angles and phase
- Higgs sector:
  - 2 parameters: μ, λ
- **Total: 19 parameters**

Unification?

Flavour?

Mass?

1973/4

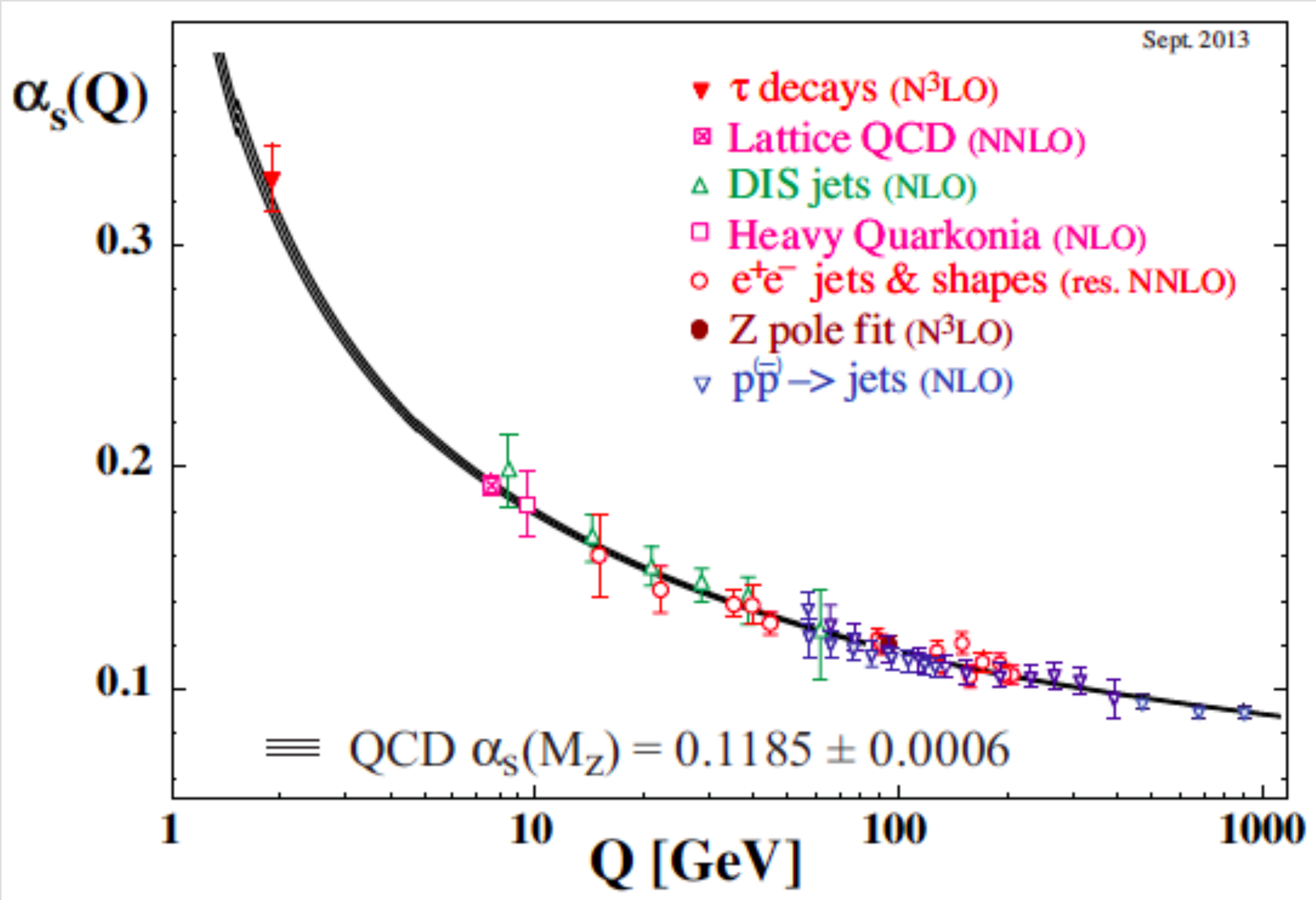
Towards Grand Unification

Pati & Salam
Georgi & Glashow
Georgi, Quinn & Weinberg

- The three Standard Model gauge couplings are different: $g_3 >> g_2, g'$
- Ratio $\sin^2\theta_W \equiv \frac{g'^2}{g'^2 + g_2^2}$ is free parameter in Standard Model
- All couplings vary energy scale, calculable using renormalisation group
- Best known is decrease of $\alpha_s \equiv \frac{g_3^2}{4\pi}$, "asymptotic freedom"
- Offers prospect of unifying couplings at high energy, as in simple group structure, and predicting $\sin^2\theta_W$

Strong Coupling "Constant" …

- … is not constant: weaker at higher energies



- **Asymptotic freedom**

Towards Grand Unification

- At one-loop order without/**with** supersymmetry:

$$b_i = \begin{pmatrix} 0 \\ -\frac{22}{3} \\ -11 \end{pmatrix} + N_g \begin{pmatrix} \frac{4}{3} \\ \frac{4}{3} \\ \frac{4}{3} \end{pmatrix} + N_H \begin{pmatrix} \frac{1}{10} \\ \frac{1}{6} \\ 0 \end{pmatrix}$$

$$b_i = \begin{pmatrix} 0 \\ -6 \\ -9 \end{pmatrix} + N_g \begin{pmatrix} 2 \\ 2 \\ 2 \end{pmatrix} + N_H \begin{pmatrix} \frac{3}{10} \\ frac12 \\ 0 \end{pmatrix}$$

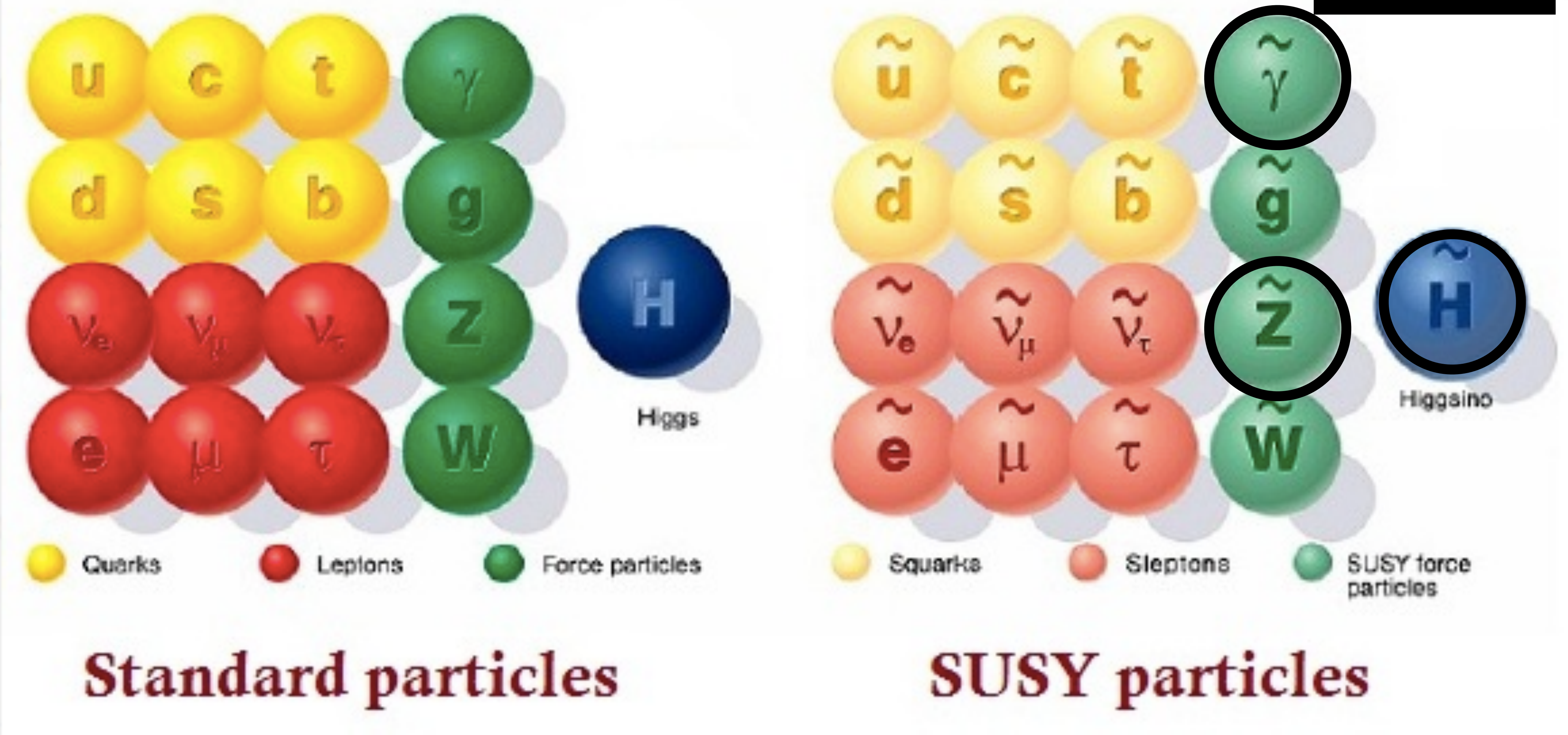
- At two-loop order without/**with** supersymmetry:

$$b_{ij} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & -\frac{136}{3} & 0 \\ 0 & 0 & -102 \end{pmatrix} + N_g \begin{pmatrix} \frac{19}{15} & \frac{3}{5} & \frac{44}{15} \\ \frac{1}{5} & \frac{49}{3} & 4 \\ \frac{4}{30} & \frac{3}{2} & \frac{76}{3} \end{pmatrix} + N_H \begin{pmatrix} \frac{9}{50} & \frac{9}{10} & 0 \\ \frac{3}{10} & \frac{13}{6} & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$b_{ij} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & -24 & 0 \\ 0 & 0 & -54 \end{pmatrix} + N_g \begin{pmatrix} \frac{38}{15} & \frac{6}{5} & \frac{88}{15} \\ \frac{2}{5} & 14 & 8 \\ \frac{11}{5} & 3 & \frac{68}{3} \end{pmatrix} + N_H \begin{pmatrix} \frac{9}{50} & \frac{9}{10} & 0 \\ \frac{3}{10} & \frac{7}{2} & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

Minimal Supersymmetric Extension of the Standard Model

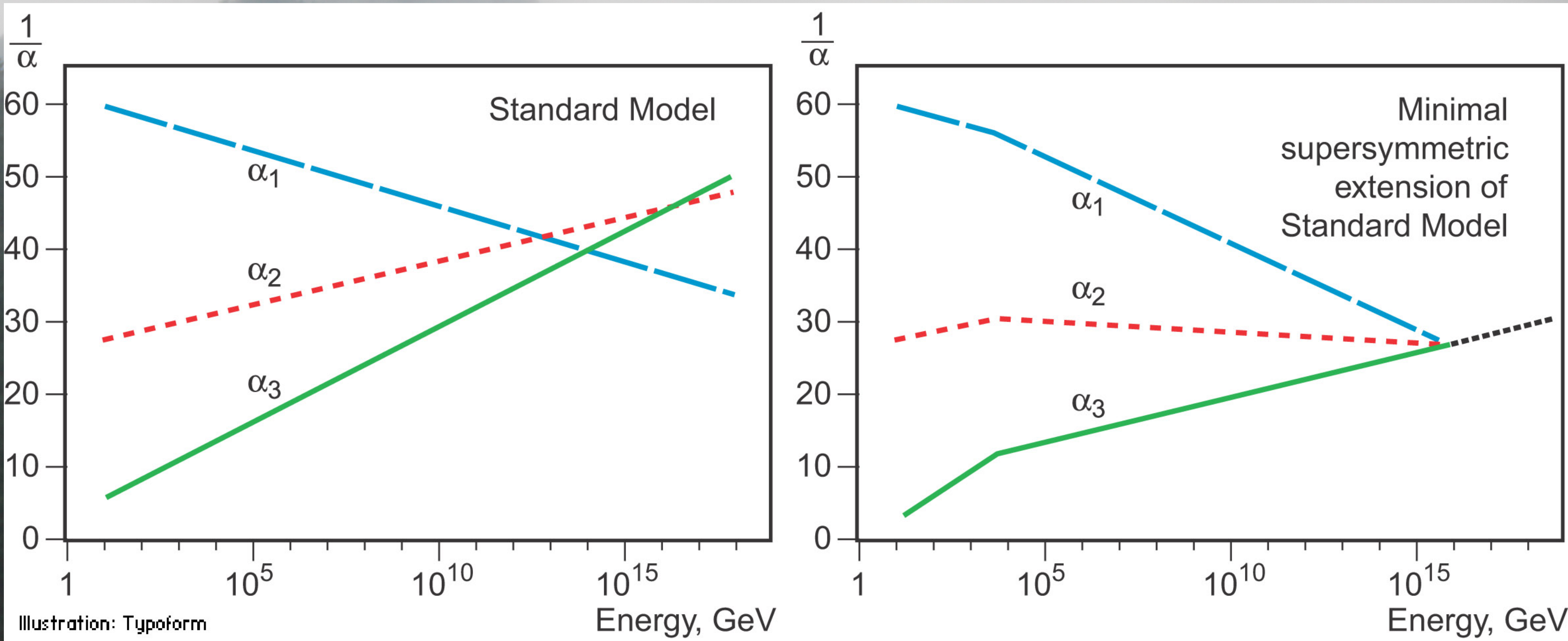
Dark Matter?



1974

Georgi, Quinn & Weinberg

Grand Unification of Couplings



Almost works with just Standard Model particles

Better with supersymmetric particles

Electroweak Mixing Angle

- Related to ratio of SU(2), U(1) couplings:

$$\sin^2\theta(m_Z) = \frac{g'^2}{g_2^2 + g'^2} = \frac{3}{5}\frac{g_1^2(m_Z)}{g_2^2(m_Z) + \frac{3}{5}g_1^2(m_Z)}$$

- At one loop:

$$\sin^2\theta(m_Z) = \frac{1}{1+8x}\left[3x + \frac{\alpha_{em}(m_Z)}{\alpha_3(m_Z)}\right] = \frac{1}{5}\left(\frac{b_2 - b_3}{b_1 - b_2}\right)$$

- One-loop coefficients w'out/**with** supersymmetry:

$$\begin{array}{rcccl}
\frac{4}{3}N_G - 11 & \leftarrow & b_3 & \rightarrow & 2N_G - 9 = -3 \\
\frac{1}{6}N_H + \frac{4}{3}N_G - \frac{22}{3} & \leftarrow & b_2 & \rightarrow & \frac{1}{2}N_H + 2N_G - 6 = +1 \\
\frac{1}{10}N_H + \frac{4}{3}N_G & \leftarrow & b_1 & \rightarrow & \frac{3}{10}N_H + 2N_G = \frac{33}{5} \\
\frac{23}{218} = 0.1055 & \leftarrow & x & \rightarrow & \frac{1}{7}.
\end{array}$$

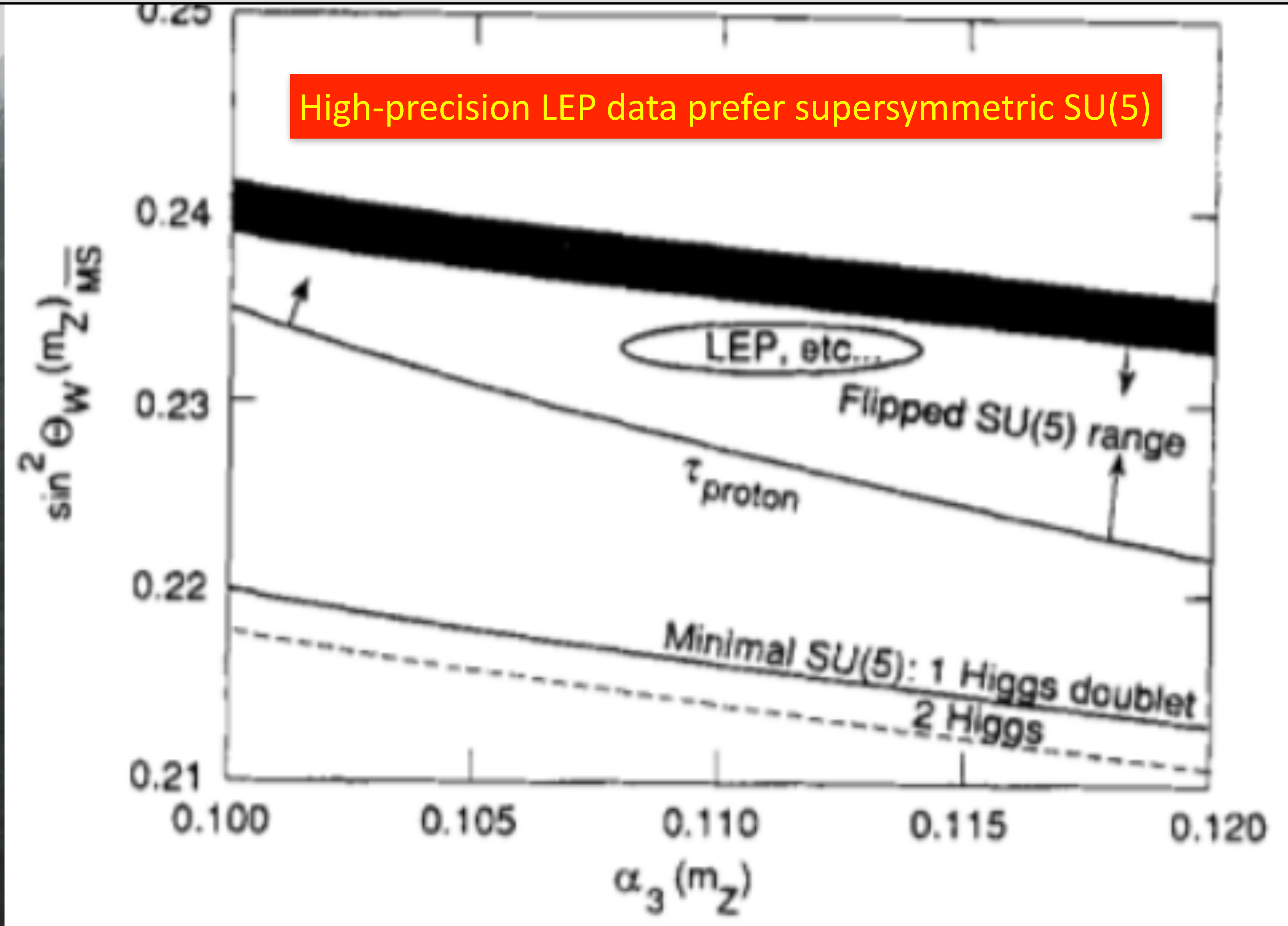
- Data:

$$x = \frac{1}{6.92 \pm 0.07}$$

1991

Ellis, Kelley & Nanopoulos

Prediction vs Measurement of $\sin^2\theta_W$



1974

Georgi & Glashow

Simplest Grand Unified Theory

- Electromagnetic charge embedded in simple group: charge quantized $\sum_{q,\ell} Q_i = 3Q_u + 3Q_d + Q_e = 0$
- Minimal model: SU(5)
- Fermions of a single generation accommodated

$$\bar{5} : (\psi_i)_L = \begin{pmatrix} \bar{d}_1 \\ \bar{d}_2 \\ \bar{d}_3 \\ e^- \\ -\nu_e \end{pmatrix}_L \quad 10 : (\chi^{ij})_L = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & \bar{u}_3 & -\bar{u}_2 & u_1 & d_1 \\ -\bar{u}_3 & 0 & \bar{u}_1 & u_2 & d_2 \\ u_2 & -\bar{u}_1 & 0 & u_3 & d_3 \\ -u_1 & -u_2 & -u_3 & 0 & e^+ \\ -d_1 & -d_2 & -d_3 & -e^+ & 0 \end{pmatrix}_L$$

- "Explain" "random" quantum numbers
- **Renormalization prediction** $\sin^2\theta_W \simeq 0.22$

Other Grand Unified Theories

- Seek simple gauge group (single coupling) with chiral representations (parity violation)
- **SU(5)** is only suitable group of rank 4 (number of simultaneously diagonalisable generators)
- Only possible group of rank 5 is **SO(10)**
- Fermions of each generation in 16-dimensional representation, with right-handed neutrino
- Possible group of rank 6 is E_6
    - Each generation in 27-dimensional representation
- Appears in compactifications of string theory

1977

Quark and Lepton Masses

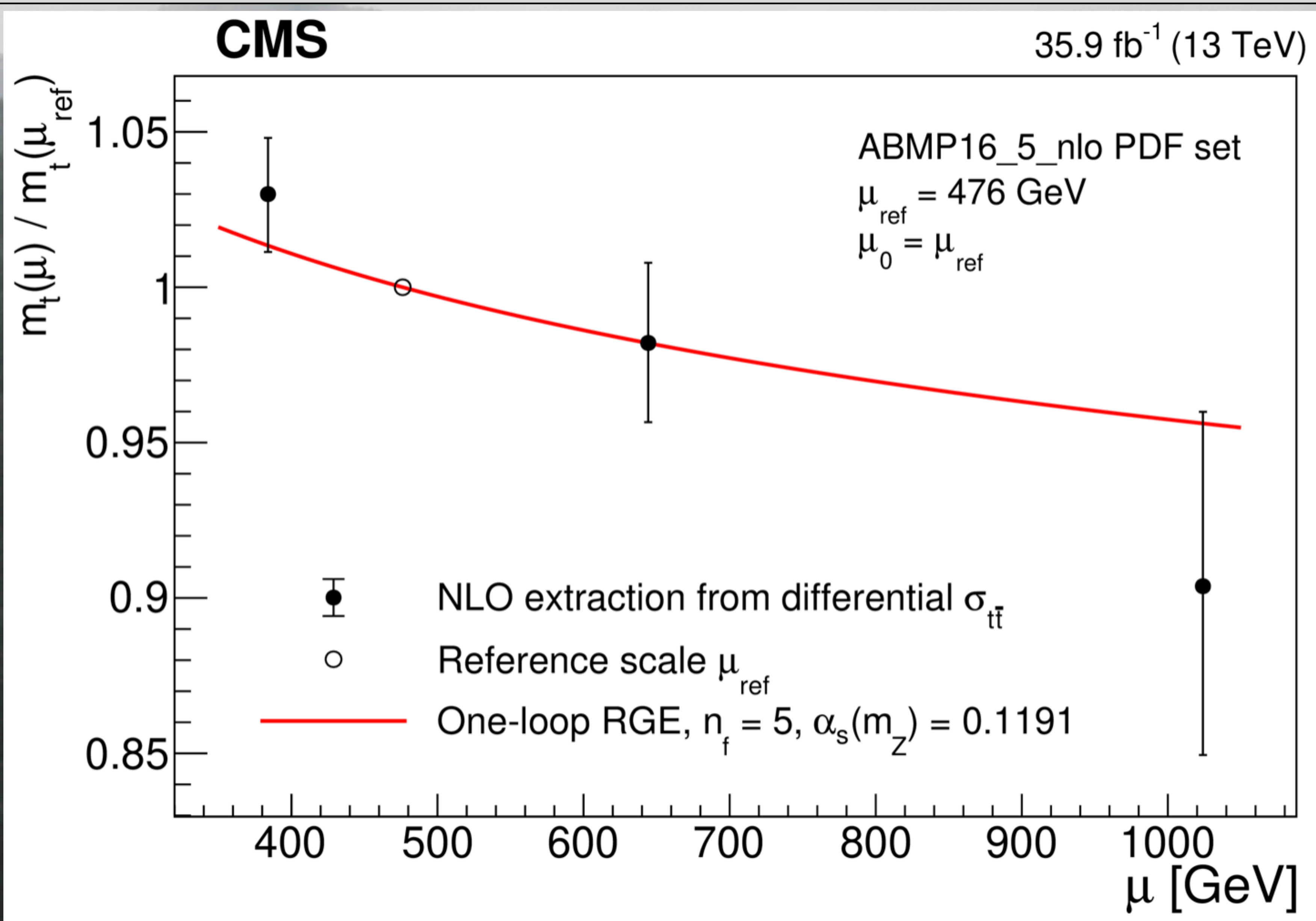
- Also vary with moment/energy scale where you measure them
- Could they be equal at some fundamental level?
  - e.g., in grand unified theory such as SU(5)
- One-loop renormalization:

Chanowitz, JE & Gaillard

$$\frac{m_b}{m_\tau} \simeq \left[\ln\left(\frac{m_b^2}{m_X^2}\right)\right]^{\frac{12}{33-2N_q}}$$

- Successful **PREdiction** of bottom mass
- Not so successful for lighter quarks/leptons

Running of the Top Quark Mass



1977

Chanowitz, JE & Gaillard

Prediction of the Bottom Quark Mass

- Our paper:
  - May 1977
- Discovery of b quark:
  - June 1977
- Proof correction:
  - "2 to 5" becomes 2605!

Nuclear Physics B128 (1977) 506–536

THE PRICE OF NATURAL FLAVOUR CONSERVATION IN NEUTRAL WEAK INTERACTIONS

Michael S. CHANOWITZ *, John ELLIS and Mary K. GAILLARD **
CERN, Geneva

Received 20 May 1977
(Revised 11 July 1977)

The natural conservation of flavours to $O(G_F^2)$ in neutral weak interactions severely constrains choices of gauge groups as well as their fermion representations. In the absence of exactly conserved quantum numbers other than charge, and of $|\Delta Q| \geqslant 2$ charged currents, essentially the only weak and electromagnetic gauge groups whose neutral interactions naturally conserve all flavours are $SU(2)_L \otimes U(1)$ and $SU(2)_L \otimes [U(1)]^2$. The plausible extensions of these gauge groups to grand unified models including the strong interactions are based on SU(5) and SO(10) respectively. Making the SU(5) model completely natural, including in the Higgs sector, gives the prediction $m_d/m_e \simeq m_s/m_\mu \simeq m_b/m_\tau \simeq 2605$ where τ is the probable new heavy lepton and b is the conjectured third flavour of charge $-\frac{1}{3}$ quark. The SO(10) model contains a potential $SU(2)_L \otimes SU(2)_R \otimes U(1)$ weak and electromagnetic gauge group, and has a complicated Higgs structure which does not naturally conserve quark flavours.

Search for Proton Decay

- Key prediction of grand unified theories
- Via $\frac{q\,q\,q\,\bar{\ell}}{m_X^2}$ interaction
- Very sensitive to mass of GUT boson X: $m_X \sim 10^{14-15}$ GeV in minimal SU(5)
- Preferred decay mode in minimal SU(5) model: $p \rightarrow \pi^0 e^+$, also $p \rightarrow \pi^+ \bar{\nu}, n \rightarrow \pi^- e^+$, …
- Motivated first generation of large underground water Čerenkov detectors (KamiokaNDE, IMB)

1983-1995

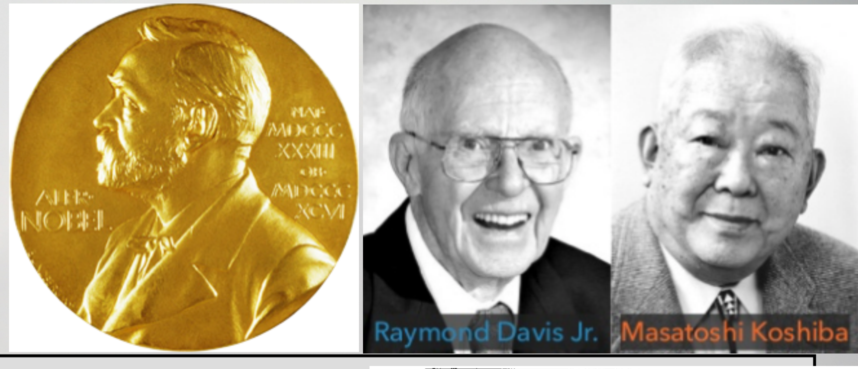
KamiokaNDE Experiment

Water Čerenkov detector

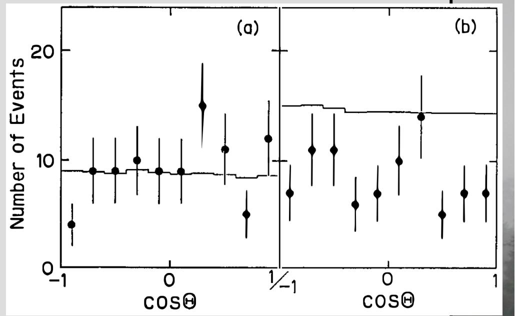
Built to look for proton decay

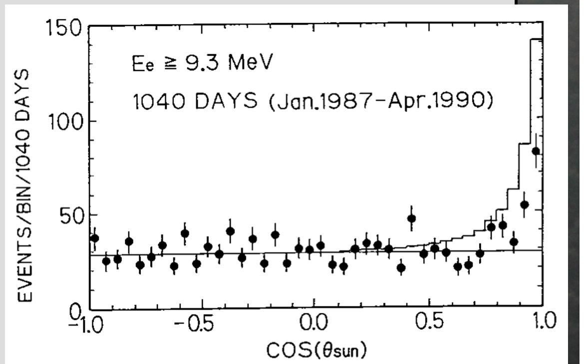
Proton decay not observed, but ...

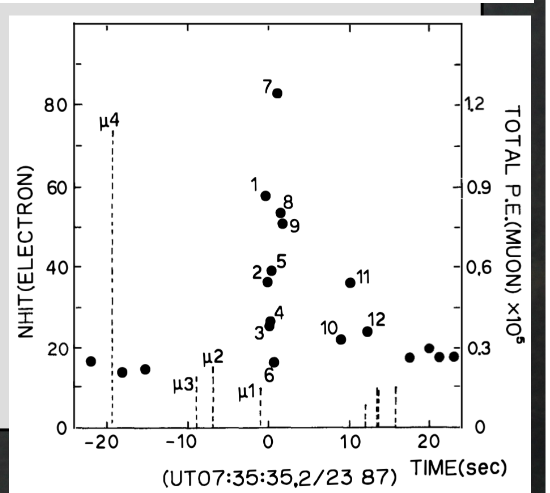
Astrophysical Neutrinos



- Collisions of cosmic rays in atmosphere
  - KamiokaNDE: deficit of muon neutrinos
- The Sun
  - Observed by Davis, 1/3 expected flux
  - KamiokaNDE sees 1/2 expected flux
- Supernovae
  - KamiokaNDE, IMB: neutrinos from SN 1987A
- Active galactic nuclei
  - Detection still tentative

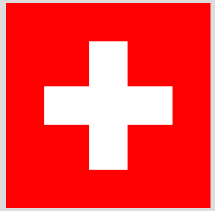






Neutrino Masses & Mixing

- Models with ν_R, e.g., SO(10), can have neutrino mass term: $\lambda \bar{\nu}_R \nu_L H \rightarrow m_\nu = \lambda < H > = \lambda v$
- Nothing to prevent large $M_{\nu_R} \sim M_{\mathrm{GUT}}$
- "Whatever is not forbidden is compulsory"



Seesaw mass matrix: $\begin{bmatrix} 0 & m_\nu \\ m_\nu & M_{\nu_R} \end{bmatrix}$

- Suggests light neutrino masses $\mathcal{O}\left(\frac{v^2}{M_{\mathrm{GUT}}}\right) \ll m_{q,\ell}$
- Mass matrix not diagonal: mixing in general

Neutrino Oscillations

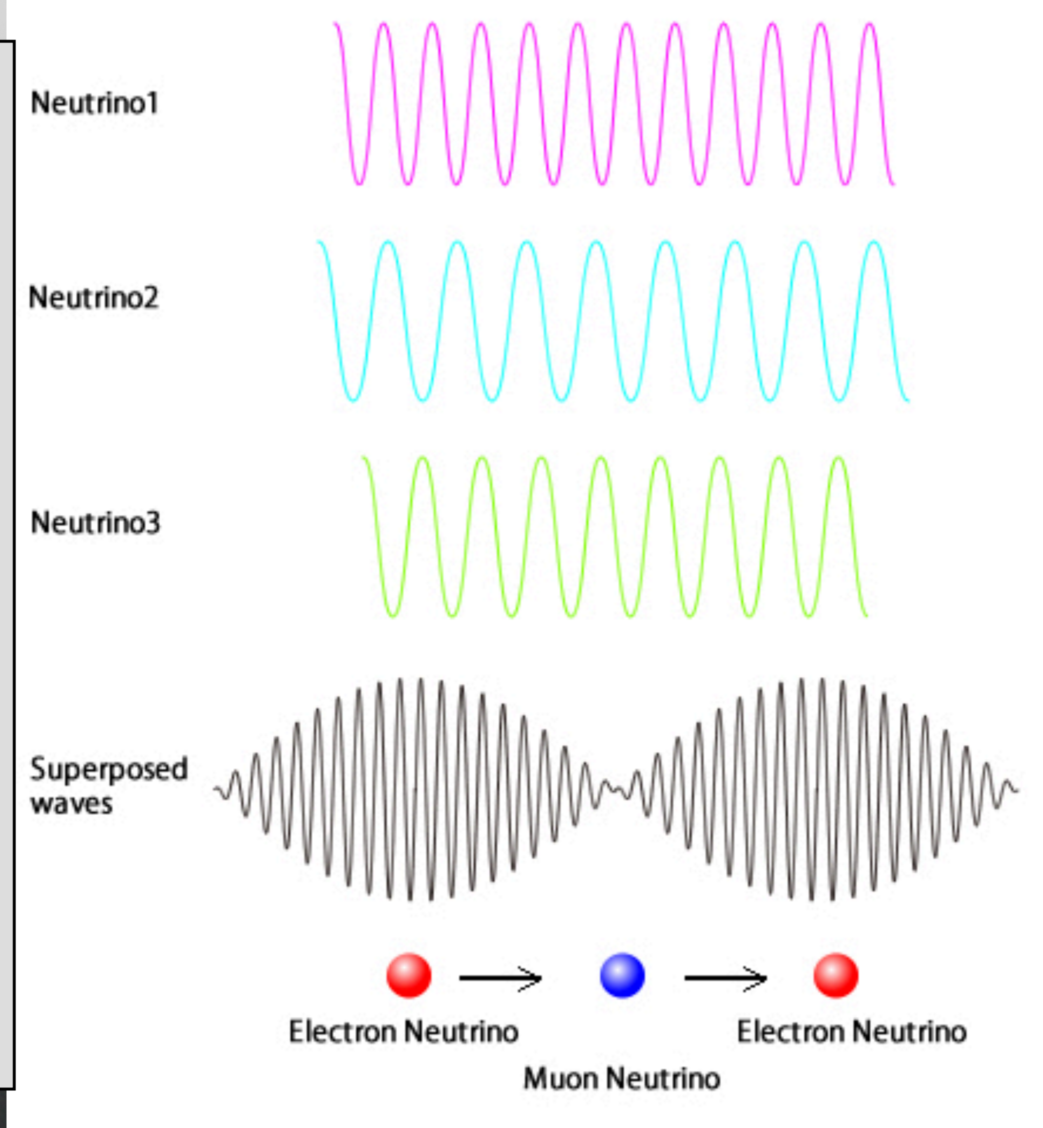
- Mixing between 2 neutrino flavours: $\begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix}$

→ oscillations with probability

$$P_{\alpha\to\beta} = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

for ν energy E over distance L

- Explain solar neutrino deficit and atmospheric muon neutrino deficit



1996

Super-Kamiokande Experiment

Still no proton decay, but ...

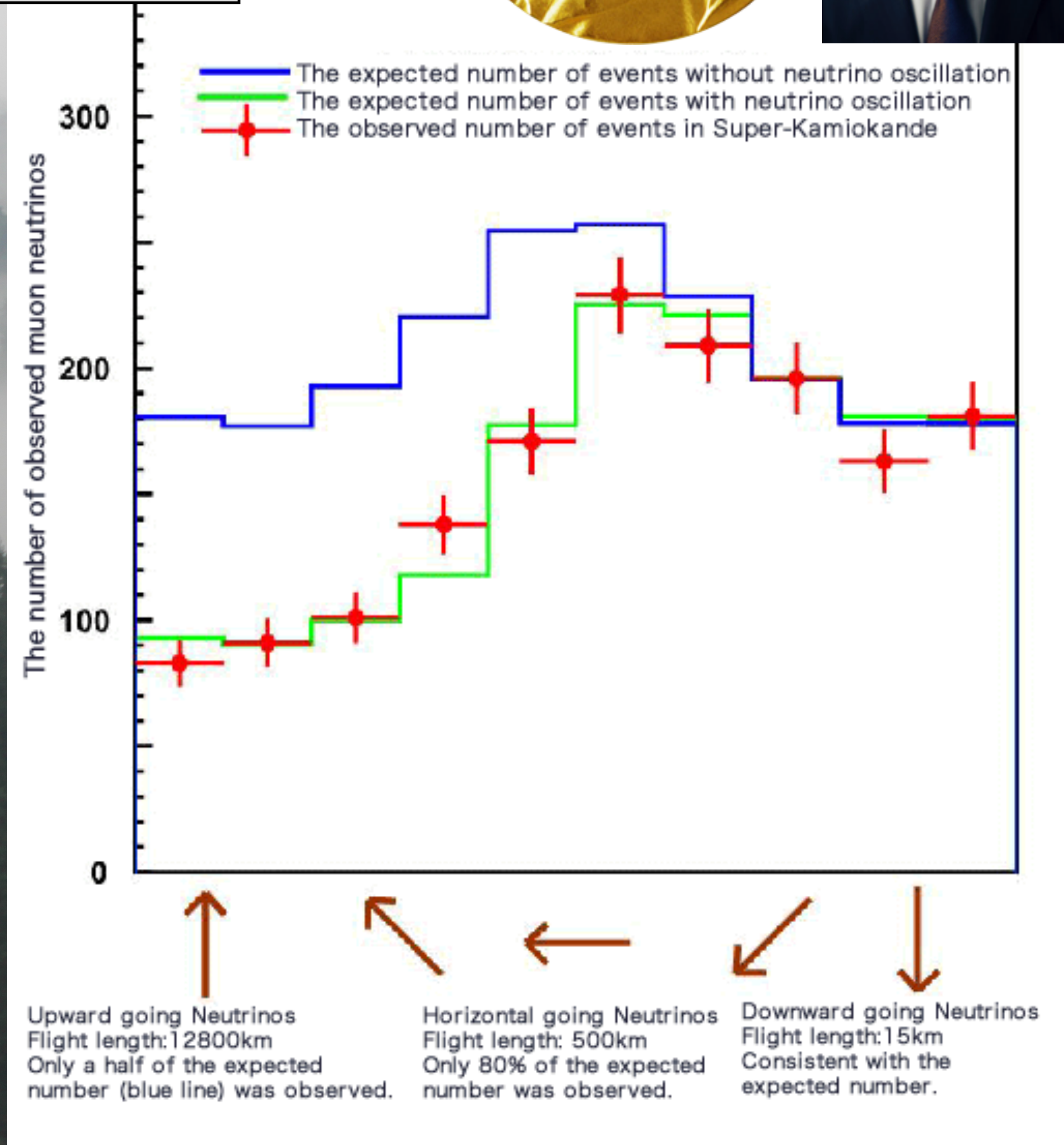
Water Čerenkov detector

Built to measure astrophysical neutrinos

1998

Atmospheric Neutrino Oscillations

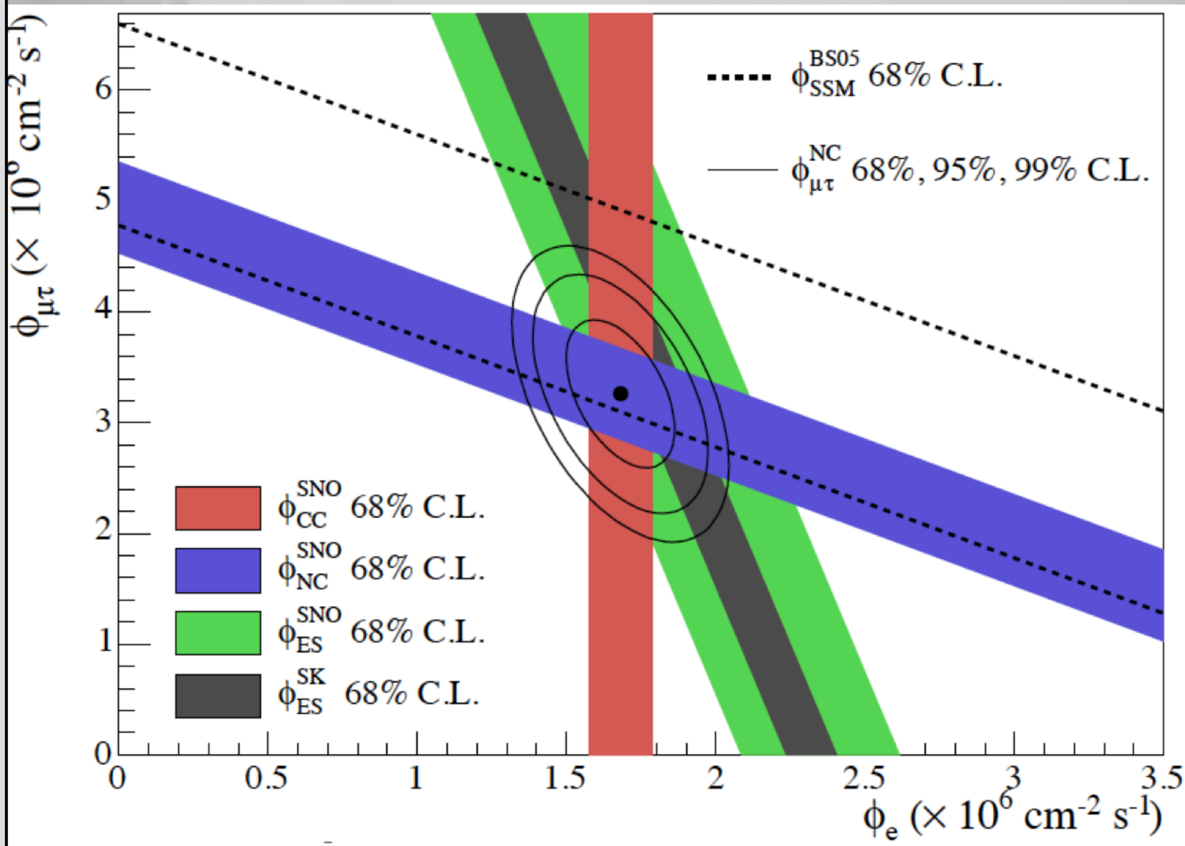
- Flux of downward muon neutrinos as expected
- Reduced flux of upward muon neutrinos
- Neutrino oscillations!



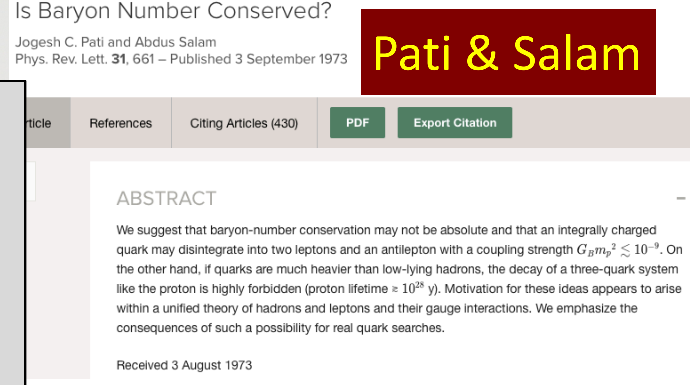
2001

Solar Neutrino Oscillations

- Flux of electron neutrinos < expected
- Compensated by flux of muon & tau neutrinos
- Total flux ~ standard solar model



Why (we still think that) Protons are not Forever


Is Baryon Number Conserved?

Jogesh C. Pati and Abdus Salam

Phys. Rev. Lett. **31**, 661 – Published 3 September 1973

ABSTRACT

We suggest that baryon-number conservation may not be absolute and that an integrally charged quark may disintegrate into two leptons and an antilepton with a coupling strength $G_B m_p{}^2 \lesssim 10^{-9}$. On the other hand, if quarks are much heavier than low-lying hadrons, the decay of a three-quark system like the proton is highly forbidden (proton lifetime $\gtrsim 10^{28}$ y). Motivation for these ideas appears to arise within a unified theory of hadrons and leptons and their gauge interactions. We emphasize the consequences of such a possibility for real quark searches.

Received 3 August 1973


Unity of All Elementary-Particle Forces

Howard Georgi and S. L. Glashow

Phys. Rev. Lett. **32**, 438 – Publishe

ABSTRACT

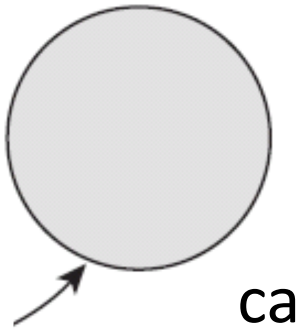
Strong, electromagnetic, and weak forces are conjectured to arise from a single fundamental interaction based on the gauge group SU(5).

Received 10 January 1974

- Grand unified theories proposed in 1973/4, predicted baryon decay
- Black holes have no memory of baryon # (B)
  - Quantum # conserved only if gauge symmetry
  - e.g., U(1) gauge symmetry & electric charge
- “Whatever is not forbidden is compulsory”
- B violated by non-perturbative effects in SM
- B would be violated by magnetic monopoles
- No global symmetries in string theory

Black Holes violate Baryon Number

- Properties of black holes determined by mass, spin, electric charge (colour), thermodynamics
- Black holes 'forget' global symmetries like B



Black holes can decay → baryons

- Black holes decay, must produce baryons

1976

Proton Decay via Gravitational Interactions?

- Four-fermion interaction ~ Newton constant

  $G_N = 1/m_P^2$, $m_P \sim 10^{19}$ GeV

- Rate ~ $G_N^2 \times (\text{GeV})^5$
- Lifetime ~ 10^{45} yrs

Zeldovich

Volume 59A, number 4 PHYSICS LETTERS 13 December 1976

A NEW TYPE OF RADIOACTIVE DECAY: GRAVITATIONAL ANNIHILATION OF BARYONS

Ya.B. ZELDOVICH

Institute of Applied Mathematics, Academy of Sciences of the USSR, Minsskaja pl. 4, Moscow 125047, USSR

Received 28 September 1976

Gravitational collapse on an elementary particle level is not excluded. It will be observed as a new type of radioactivity, violating baryon conservation.

The modern ideas of gravitational theory applied to elementary particles lead to the possibility of new types of spontaneous processes. These processes look like the annihilation of baryons, with their rest mass transformed into the energy of neutral particles. In principle even a single nucleon can undergo such a transformation, for example, $P \to e^+ + \pi^0$ or $N \to \nu + \pi^0$ or $\to e^+ + \pi^-$. This conclusion is based on the well known properties of the closed metric: a three dimensionally closed manifold is able to have a net baryonic charge (but not an electric charge). It has no mass or momentum, being topologically disconnected from our space.

Therefore we imagine baryons or a baryon going into such a state; every individual world line of baryonic charge has no end, but disappears from our space. Energy conservation in our space leads to the birth of a neutral cloud of particles with energy equal to that of the disappeared baryons.

The theory of primordial black hole formation [1–3] plus that of black hole evaporation [4] make this process very plausible. Jointly the formation of a black hole from matter and its evaporation leads to what is observationally baryon non-conservation. But if (or when) the mass of the black hole is equal or less than the Planckian one $m_p \cdot (\propto G^{-1/2}$, where G is the gravitational constant, $\hbar = c = 1$, $m_p = 10^{-5}$ g) the evaporation goes in one quantum jump. At densities equal or less than nuclear, the formation of a black hole with $m \gtrsim m_p$ is a tunnel process with an immense negative exponent. But with very small masses of the order of $m = 10^{-18}$ m_p one can guess that both processes: black hole formation and its evaporation could be viewed as one quantum jump. Its probability is evaluated as being small like a power* of $G \cdot m^2$.

Actually in a gas of baryons the probability per baryon must be proportional to the density of other baryons n and (by phase space argument) to the square of the energy. Dimensional analysis leads to the formula $W = n \cdot m^2 \cdot G$. Taking $n \approx m^3$ as an approximation for nuclei we obtain

$$W \sim m \cdot (G \cdot m^2)^2 \sim \frac{mc^2}{\hbar}\left(\frac{Gm^2}{\hbar c}\right)^2 \sim (10^{45}\ \text{y})^{-1}$$

obviously this does not contradict experiments [5] and is very difficult to verify. Perhaps it will be important in cosmological singularity situations.

The paper by Fomin [6] (closed world birth from vacuum) was also a source of inspiration for the above mentioned ideas.

A more detailed version of the article is in print in the Russian Journal of Experimental and Theoretical Physics.

I am grateful to V.N. Gribov, M.A. Markov, L.B. Okun and A.A. Starobinsky for discussions.

* The m without an index is the proton mass.

References

[1] Ya.B. Zeldovich and I.D. Novikov, Astron. Zh. 43 (1966) 758.
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[3] B.J. Carr, Astrophys. J. 201 (1975) 1.
[4] S.W. Hawking, Nature 248 (1974) 30.
[5] W.P. Kropp and F. Reines, Phys. Rev. 137 (1965) B740.
[6] P.I. Fomin, Dokl. Akad. Sci. Ukr.S.S.R. A (1975) 831.

1976

Non-Perturbative B Violation in SM

VOLUME 37, NUMBER 1 PHYSICAL REVIEW LETTERS 5 JULY 1976

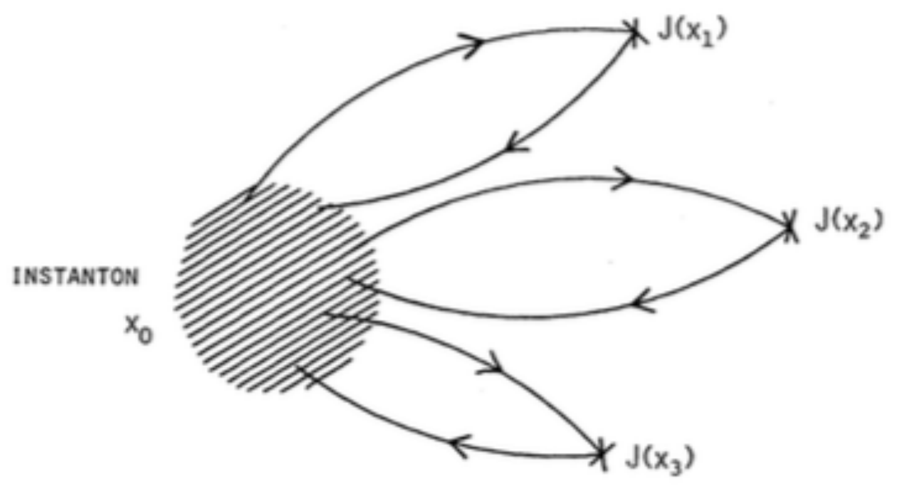
Symmetry Breaking through Bell-Jackiw Anomalies*

't Hooft

G. 't Hooft†
Department of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 22 March 1976)

In models of fermions coupled to gauge fields certain current-conservation laws are violated by Bell-Jackiw anomalies. In perturbation theory the total charge corresponding to such currents seems to be still conserved, but here it is shown that nonperturbative effects can give rise to interactions that violate the charge conservation. One consequence is baryon and lepton number nonconservation in $V-A$ gauge theories with charm. Another is the nonvanishing mass squared of the η.

- Electroweak instantons violate B, L
- Change each of electron, muon, tau number



- Change numbers of 1st, 2nd & 3rd generation q

$\Delta B = \Delta L = 3$

- Do not give rise directly to baryon decay
- Could have played role in baryogenesis

1967

Cosmological Baryogenesis

Sakharov

- Origin of baryon asymmetry of Universe?
- Non-perturbative electroweak processes unsuppressed in early Universe
- Could convert primordial L asymmetry (partially) into B asymmetry
- L asymmetry could come from CP violation in decays of heavy (singlet) neutrinos

1987

Fukugita & Yanagida

- Requires Majorana ν (0ν2β decay?)
- **CP-violating phase ≠ oscillation phase**

1981, 1982

Monopole Catalysis of B Decay

Superheavy magnetic monopoles and decay of the proton

Rubakov

V. A. Rubakov
Institute of Nuclear Research, Academy of Sciences of the USSR

(Submitted 10 May 1981)
Pis'ma Zh. Eksp. Teor. Fiz. **33**, No. 12, 658–660 (20 June 1981)

A possible pronounced nonconservation of baryon number in interactions involving magnetic monopoles is discussed in a unified theory with SU (5) gauge group. Possible experimental consequences of this nonconservation are examined.

MONOPOLE CATALYSIS OF BARYON DECAY

Callan

Curtis G. CALLAN, Jr.[1]
Joseph Henry Laboratories, Princeton University, Princeton, NJ 08540, USA

Received 23 August 1982

In the presence of magnetic monopoles, the baryon-number-violating effects of grand unified gauge theories are not suppressed by inverse powers of the unification mass. As a result, monopoles *catalyse* proton decay at rates typical of the strong interactions. This phenomenon is caused by boundary conditions which must be imposed on fermion fields at the monopole core. They mix quarks and leptons and cause the monopole to have indefinite baryon number. We present a simplified account of these phenomena as well as their implications for proton decay and monopole search experiments.

- GUTs have magnetic monopoles
- Symmetry restored in monopole core, quarks sucked in
- Large rate for ΔB in monopole scattering

$$u_1 + M \to M + \bar{u}_2 + \bar{d}_3 + e^+$$

- **Are there any monopoles in our Universe?**

1979

Weinberg

B is Accidental Symmetry of the SM

- The Standard Model does not allow any B-violating interactions of dimension ≤ 4
- But there are B-violating interactions of dimension ≥ 6
- Would be suppressed by some high mass scale as in GUTs ~ $1/M^2$

$$O^{(1)}_{abcd} = (\bar{d}^{C}_{\alpha a R} u_{\beta b R})(\bar{q}^{C}_{i \gamma c L} l_{j d L})\epsilon_{\alpha\beta\gamma}\epsilon_{ij},$$

$$O^{(2)}_{abcd} = (\bar{q}^{C}_{i \alpha a L} q_{j \beta b L})(\bar{u}^{C}_{\gamma c R} l_{d R})\epsilon_{\alpha\beta\gamma}\epsilon_{ij},$$

$$O^{(3)}_{abcd} = (\bar{q}^{C}_{i \alpha a L} q_{j \beta b L})(\bar{q}^{C}_{k \gamma c L} l_{l d L})\epsilon_{\alpha\beta\gamma}\epsilon_{ij}\epsilon_{kl},$$

$$O^{(4)}_{abcd} = (\bar{q}^{C}_{i \alpha a L} q_{j \beta b L})(\bar{q}^{C}_{k \gamma c L} l_{l d L})\epsilon_{\alpha\beta\gamma} \times (\vec{\tau}\epsilon)_{ij}\cdot(\vec{\tau}\epsilon)_{kl},$$

$$O^{(5)}_{abcd} = (\bar{d}^{C}_{\alpha a R} u_{\beta b R})(\bar{u}^{C}_{\gamma c R} l_{d R})\epsilon_{\alpha\beta\gamma},$$

$$O^{(6)}_{abcd} = (\bar{u}^{C}_{\alpha a R} u_{\beta b R})(\bar{d}^{C}_{\gamma c R} l_{d R})\epsilon_{\alpha\beta\gamma}.$$

Baryon- and Lepton-Nonconserving Processes

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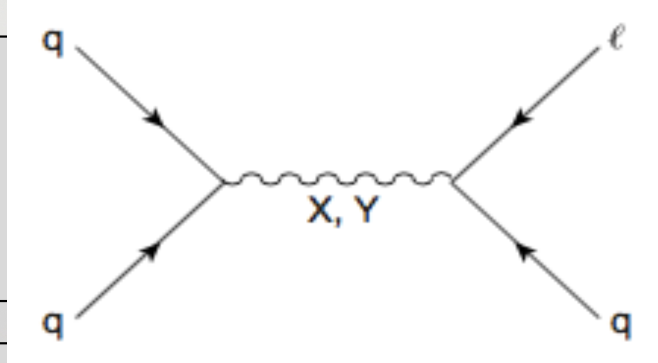
(Received 13 August 1979)

A number of properties of possible baryon- and lepton-nonconserving processes are shown to follow under very general assumptions. Attention is drawn to the importance of measuring μ^+ polarizations and $\bar{\nu}_e/e^+$ ratios in nucleon decay as a means of discriminating among specific models.

1974

Georgi & Glashow

B Decay in Original SU(5)

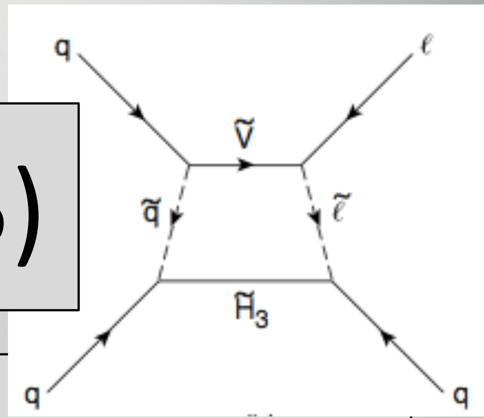


- Prediction for m_b in terms of m_τ suggests identification of 3rd-generation q and l: {b, t, τ}
  - Analogous predictions for 1st and 2nd generations qualitative, not quantitative
- Suggests (small) mixing corrections to naive generation structure: p ➔ $e^+\pi^0$, $\nu\pi^+$, μ^+K^0, νK^+
- $$\left(\epsilon_{ijk}u_{R_k}\gamma_\mu u_{L_j}\right) \quad \frac{g_X^2}{8m_X^2} \quad (2e_R\ \gamma^\mu\ d_{L_i} + e_L\ \gamma^\mu\ d_{R_i})$$ $$\left(\epsilon_{ijk}u_{R_k}\gamma_\mu d_{L_j}\right) \quad \frac{g_Y^2}{8m_X^2} \quad (\nu_L\ \gamma^\mu\ d_{R_i})\ .$$ so that $\tau_p = \frac{1}{c}\frac{m_X^4}{m_p^5}$ where $m_X \simeq (1 \text{ to } 2) \times 10^{15} \times \Lambda_{QCD}$
- Lifetime too short? $$\tau(p \to e^+\pi^0) \simeq 2 \times 10^{31\pm1} \times \left(\frac{\Lambda_{QCD}}{400 \text{ MeV}}\right)^4 \quad y$$

1982

Dimopoulos, Raby & Wilczek

B Decay in Supersymmetric SU(5)



- B-violating operators of dimension 5 with squarks, sleptons: $qq\tilde{q}\tilde{l}$
- Dressed with Higgsino, Wino exchange ➔ operators of dimension 6 with quarks, sleptons

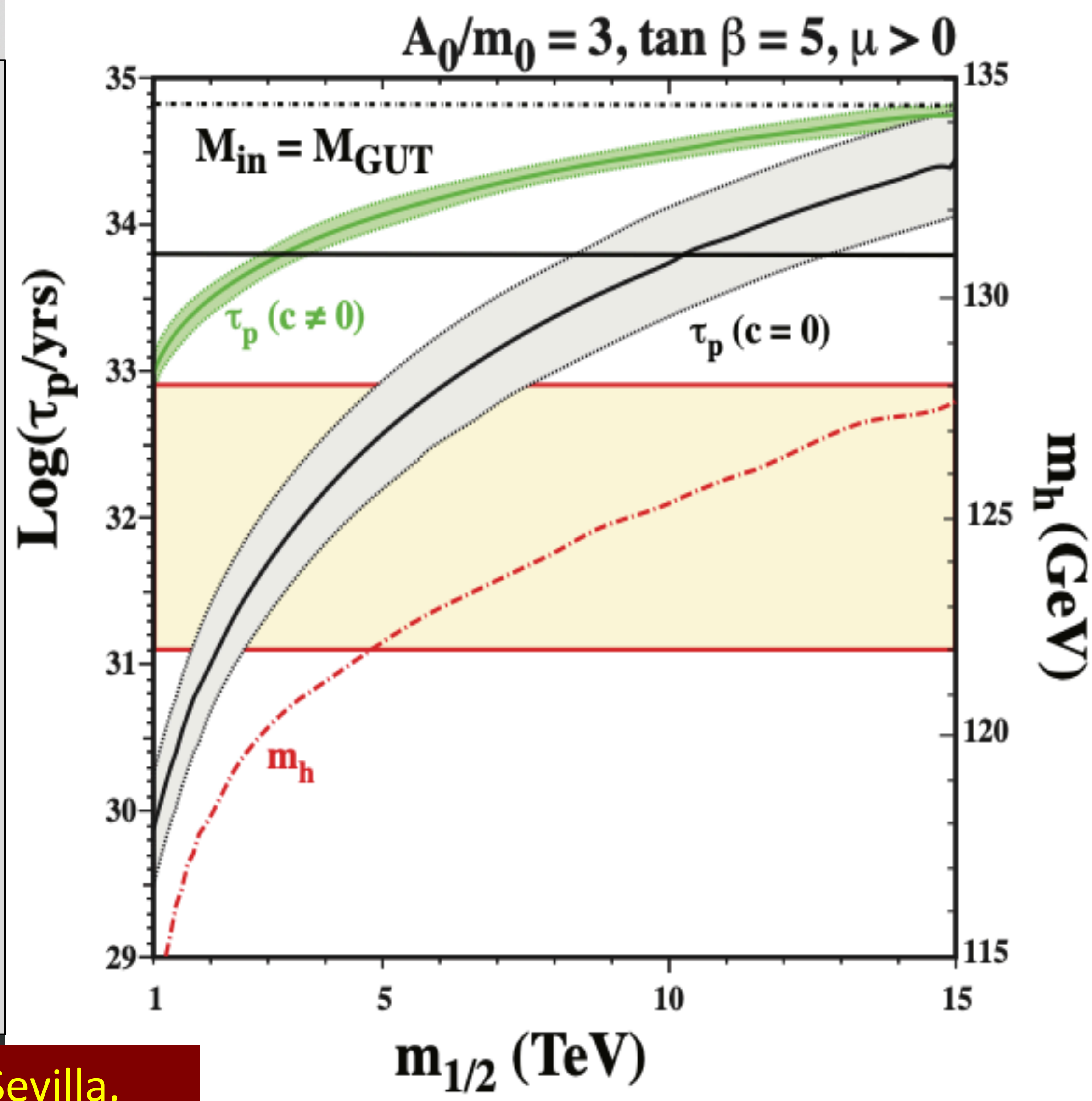
$$\mathcal{L}(p \to K^+ \bar{\nu}_i) = C_{RL}(usd\nu_i)\left[\epsilon_{abc}(u_R^a s_R^b)(d_L^c \nu_i)\right] + C_{RL}(uds\nu_i)\left[\epsilon_{abc}(u_R^a d_R^b)(s_L^c \nu_i)\right] + C_{LL}(usd\nu_i)\left[\epsilon_{abc}(u_L^a s_L^b)(d_L^c \nu_i)\right] + C_{LL}(uds\nu_i)\left[\epsilon_{abc}(u_L^a d_L^b)(s_L^c \nu_i)\right]$$

- Coefficient $G_X \to \mathcal{O}\left(\frac{\lambda^2 g^2}{16\pi^2}\right) \frac{1}{m_{\tilde{H}_3} \tilde{m}}$ $\quad m_X \simeq 2 \times 10^{16}$ GeV
- Antisymmetry in colour indices ➔u,d,s quarks
- Preferred decay modes: $p \to \bar{\nu} K^+\,, \quad n \to \bar{\nu} K^0\,, \quad \ldots$

2019

B Decay in Supersymmetric SU(5)

- Proton lifetime goes up with supersymmetry scale $m_{1/2}$
- Higgs mass bounds $m_{1/2} < 15$ TeV
- Proton lifetime < 10^{35} years



JE, Evans, Nagata, Olive & Velasco-Sevilla, arXiv:1912.04888, *see also* arXiv:2011.03554

Grand Unification in String Theory?

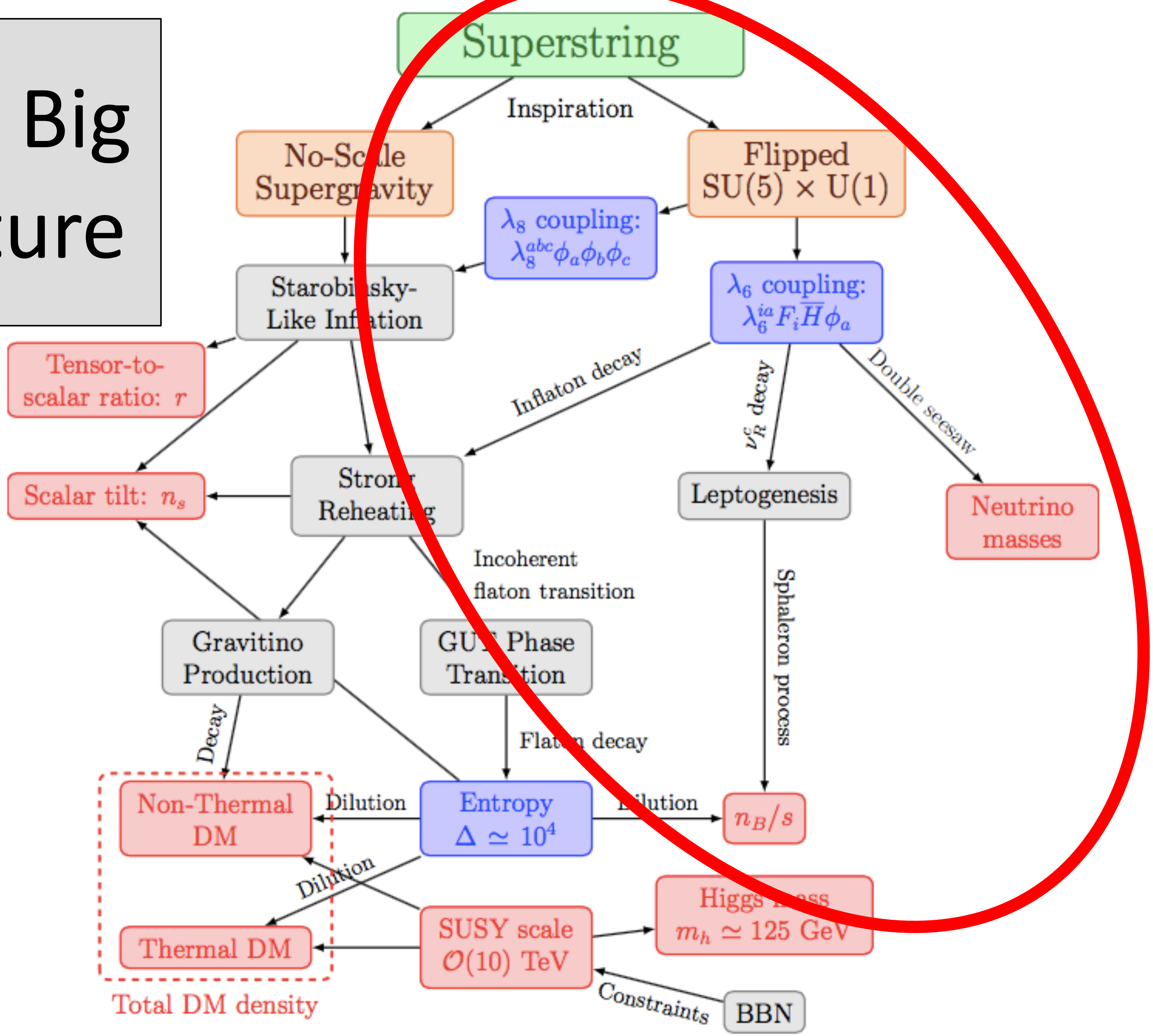
- Original supersymmetric compactifications of weakly-coupled $\mathrm{E}_8 \times \mathrm{E}_8$ heterotic string suggested E_6 GUT to get chiral representations (parity violation)
- Followed by other heterotic constructions
- None able to get adjoint Higgs, e.g., **24** of SU(5)
- GUT (almost) that does not need adjoint Higgs
  - **"Flipped SU(5)" =** $\mathrm{SU}(5) \times \mathrm{U}(1) \in \mathrm{SO}(10)$
- Quark and lepton assignments flipped: $u \leftrightarrow d, \ell \leftrightarrow \nu$
- Fermions in **16** representation $\ni \nu_R$
- Subsequently strongly-coupled models, brane models

Flipped ? Almost ? A Model of Everything Below the Planck Scale

- Simple GUT models (SU(5), SO(10)) not obtained from weakly-coupled string
  - They need adjoint Higgs, …
- **Flipped SU(5)×U(1) derived**, has advantages
  - Small (5-, 10-dimensional) Higgs representations
  - Long-lived proton, neutrino masses, leptogenesis, …
- Construct model of Starobinsky-like inflation within flipped SU(5)×U(1) framework

JE, Garcia, Nagata, Nanopoulos & Olive, arXiv:1910.11755

The Big Picture

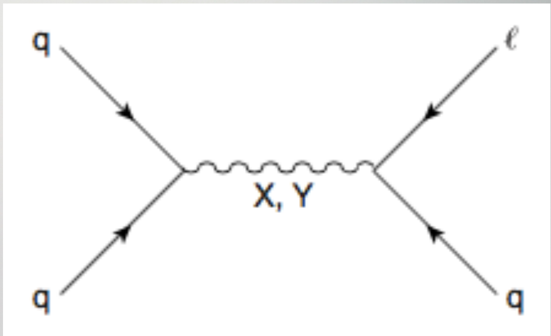


JE, Garcia, Nagata, Nanopoulos & Olive, arXiv:1910.11755

1987

Antoniadis, JE, Hagelin & Nanopoulos

B Decay in Flipped SU(5)



- Flip quark and lepton assignments in $\bar{5}$, 10

  u ←→ d, e,μ ←→ ν

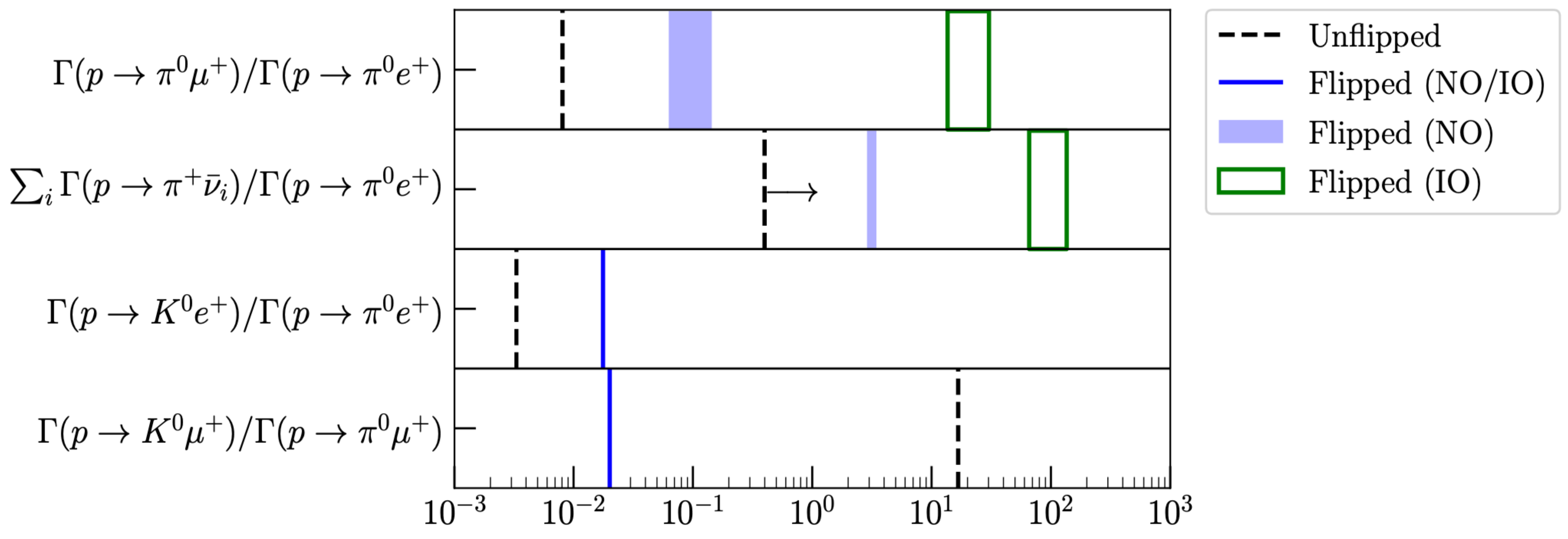
- Dimension-5 operators suppressed
- Back to dimension-6, larger $m_X \simeq 2 \times 10^{16}$ GeV
- No prediction for m_b, could change multiplet assignments
- Dominant decay could be

  $p \to e^+\pi^0$ or $p \to \mu^+\pi^0$ or $p \to \mu^+K^0$

2020

JE, Garcia, Nagata, Nanopoulos & Olive, arXiv:2003.03285

B Decay in Flipped SU(5) vs Unflipped



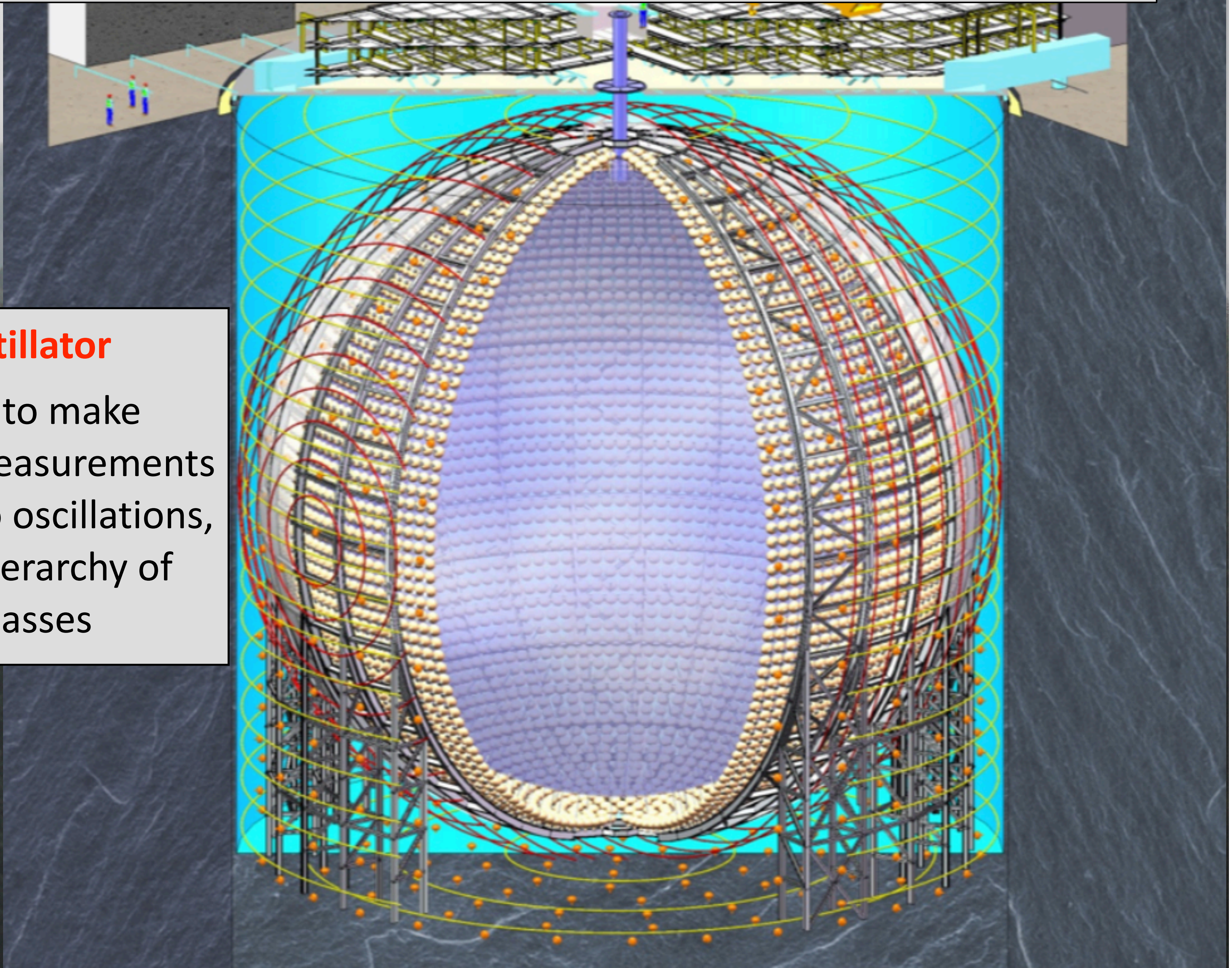
Probing different decay modes can distinguish between different models

Present & Prospective Baryon Decay Sensitivities

Current limits & prospective sensitivities of future experiments in units of 10^{33} yrs

Decay Mode	Current (90% CL)	Future (Discovery)	Future (90% CL)
$p \to K^+ \bar{\nu}$	6.6	JUNO: 12 (20) DUNE: 30 (50) Hyper-K: 20 (30)	JUNO: 19 (40) DUNE: 33 (65) Hyper-K: 32 (50)
$p \to \pi^+ \bar{\nu}$	0.39		
$p \to e^+ \pi^0$	16	DUNE: 15 (25) Hyper-K: 63 (100)	DUNE: 20 (40) Hyper-K: 78 (130)
$p \to \mu^+ \pi^0$	7.7	Hyper-K: 69	Hyper-K: 77
$n \to K^0_S \bar{\nu}$	0.26		
$n \to \pi^0 \bar{\nu}$	1.1		
$n \to e^+ \pi^-$	5.3	Hyper-K: 13	Hyper-K: 20
$n \to \mu^+ \pi^-$	3.5	Hyper-K: 11	Hyper-K: 18

JUNO Experiment

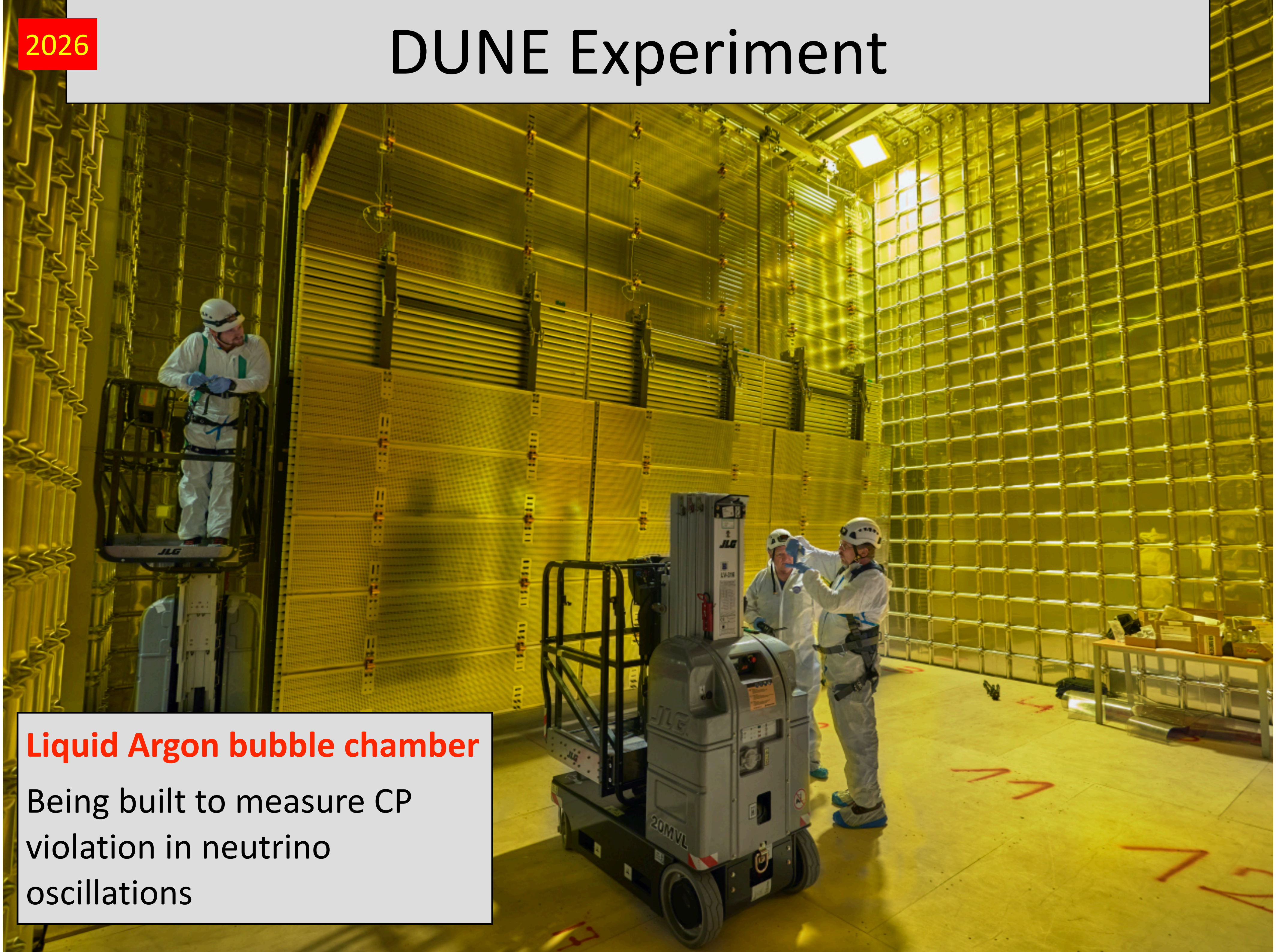


Liquid scintillator

Being built to make detailed measurements of neutrino oscillations, measure hierarchy of neutrino masses

2026

DUNE Experiment



Liquid Argon bubble chamber

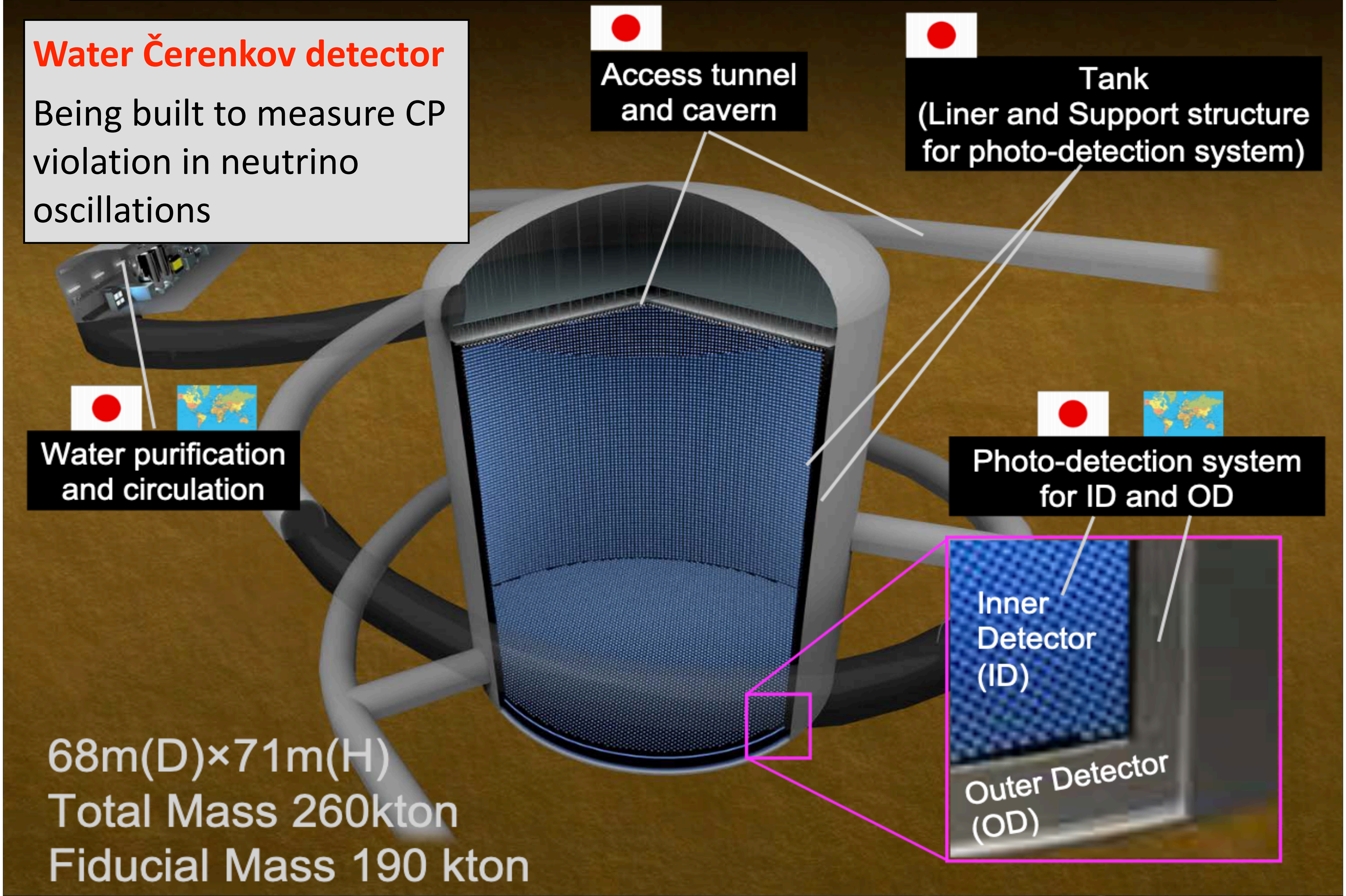
Being built to measure CP violation in neutrino oscillations

2027

Hyper-Kamiokande Experiment

Water Čerenkov detector

Being built to measure CP violation in neutrino oscillations



2027

Hyper-Kamiokande Experiment

- Approved 2020
- Civil engineering to 2025
- Installation 2026
- Data-taking from 2027
- **Am participating to support searches for proton decay**

Europe	249 members
Armenia	3
Czech	3
France	24
Germany	1
Italy	53
Poland	37
Russia	21
Spain	26
Sweden	5
Switzerland	5
Ukraine	3
UK	68 JE

Asia	138 members
India	10
Korea	18
Japan	110

Americas	52 members
Brazil	3
Canada	28
Mexico	12
USA	9

Great Irony of Physics History?

- KamiokaNDE experiment constructed to look for proton decay: discovered atmospheric ν's
  - "NDE" = nucleon decay experiment
- Super-Kamiokande discovered ν oscillations
  - A spin-off of grand unified theories
- JUNO, DUNE, Hyper-Kamiokande proposed to measure ν oscillations, look for CP violation
- **Will they discover proton decay?**
  - Or a passing magnetic monopole?
- What next if proton decay discovered?
  - Explore decay modes ➔ even larger detectors?