PHYS 6610: Graduate Nuclear and Particle Physics I

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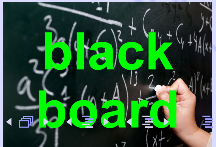
III. Descriptions

5. (Electro-)Weak Interactions: The Glashow-Salam-Weinberg Theory

Or: A Theorist's Theory

References: [phenomenology: PRSZR 10, 11, 12, 18.6; Per 7.1-6 – theory: Ryd 8.3-5; CL 11, 12; Per 7, 8, 5.4; most up-to-date: PDG 10-14 and reviews inside listings]



(a) Weak Phenomenology: Overview

Oldest trans-atomic signal: 1894
Bequerel's photographic plate

The only interaction which has been *shown* to:

- act on *all* fundamental particles (besides gravity; QED: only charged; QCD: only quarks);
- violate each of P, C and CP (i.e. also T);
- change fermion flavours (violate conservation of each quark and lepton species, sum conserved)

Signatures:

(besides parity, duh!)

- tiny cross sections at low energies: $\sigma_{\text{typ}} \sim 10^{-15} = 1\text{ fb}$;
- very narrow widths/small rates/long lifetimes: $\tau_{\text{typ}} \sim [10^{-13} \dots 10^3]\text{s}$;
- often "missing" energy & momentum: neutrinos very hard to detect.

Pauli's neutrino hypothesis letter: *"Dear Radioactive Ladies and Gentlemen, Zürich, Dec. 4, 1930 [. . .] I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. [. . .] there could exist electrically neutral particles [. . .] that have spin 1/2 and obey the exclusion principle and [. . .] do not travel with the velocity of light. The mass [. . .] should be of the same order of magnitude as the electron mass [. . .]*

Mr Debye [. . .] told me recently in Bruxelles: 'Oh, It's better not to think about this at all, like new taxes.'"

Same day, private: **Today I have done something which you never should do in theoretical physics. I have explained something which is not understood by something which can never be observed.**

Here a-historic approach: Construct from wealth of present evidence.
$\Longrightarrow$ Step I: Classify wide variety of phenomena into simple categories.

Leptonic Processes (Examples)

numbers from [PDG 2022]

Involve only leptons – rarest but cleanest $\Longrightarrow$ Use them to develop general theory!

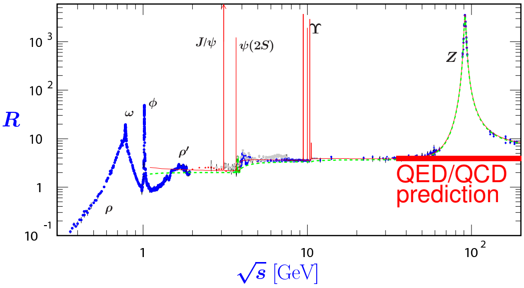
μ-Decay: $\mu^- \to e^- + \overline{\nu}_e + \nu_\mu$ $\tau \sim 10^{-6}\mathrm{s}$ Both violate ***individual*** lepton conservation,

Charge Transfer: $e^- + \nu_\mu \to \mu^- + \nu_e$ but lepton-**family** number conserved:

$$\Longrightarrow L_\mu(\mu^-) = L_\mu(\nu_\mu) = 1 = -L_\mu(\mu^+) = -L_\mu(\overline{\nu}_\mu) \text{ etc.}$$

In both, charge is transferred between leptons: **Charged-Current interaction (CC)**

The Z^0 resonance: wide, at $\sqrt{s} = 91\ \mathrm{GeV}$ in $e^+e^- \to X$ decay 20% into $\nu_e\overline{\nu}_e$, $\nu_\mu\overline{\nu}_\mu$, $\nu_\tau\overline{\nu}_\tau$ pairs.



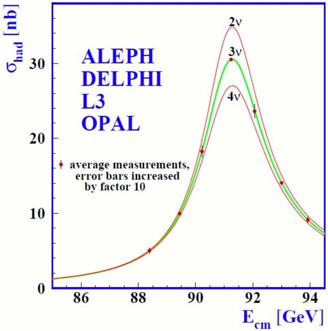
$\Longrightarrow$ Speculate weak process, mediated by $J^{PC} = 1^{--}$ boson:

Neutral-Current interaction (NC)

Determine ν rates indirectly:

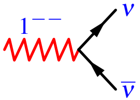
$$\Gamma_\nu = \underbrace{\Gamma_{\mathrm{tot}}}_{\text{line shape}} - \underbrace{(\Gamma_{\mathrm{hadr}} + \Gamma_{e\mu\tau})}_{\text{calorimeters}}$$

No decays like $\nu_e\overline{\nu}_\mu$ observed!



$$\Gamma[\to e^+e^-] : \Gamma[\to \mu^+\mu^-] : \Gamma[\to \tau^+\tau^-] = 1 : [1.0001 \pm 0.0024] : [1.0020 \pm 0.0032]$$

$\Longrightarrow$ Weak interaction universal for both neutrinos and charged leptons.

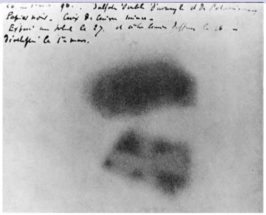


GSW: $\Gamma[\text{invisible}] = [499.0 \pm 1.5]\mathrm{MeV}$. HW 5.5: LO decay $\Gamma = \frac{g^2 M_W}{12\pi}$, $g \to \ldots$ GSW theor

Compare to $\Gamma_\nu^{\mathrm{exp}} \Longrightarrow [2.92 \pm 0.05]$ ν species with $M_\nu \ll 90\ \mathrm{GeV}$

Semi-Leptonic Processes (Examples)

Involve leptons and hadrons – most common, oldest seen.



Uranium decay unspecific: **Henri Bequerel 26 February 1896**

Neutron decay $n(udd) \to p(uud) + e^- + \overline{\nu}_e$ $\tau = [878.4 \pm 0.5]\mathrm{s}$ [PDG 2022]

i.e. $d \to u e^- \overline{\nu}_e$ $\Longrightarrow$ **Charged Current Exchange: CC**

π decay, e.g. $\pi^+(u\bar{d}) \to \mu^+ + \nu_\mu, e^+ + \nu_e$, i.e. quark process similar to proton **CC**

K decay, e.g. $K^+(u\bar{s}) \to \mu^+ + \nu_\mu, e^+ + \nu_e$, i.e. $u\bar{s} \to (s\bar{s}$ or $u\bar{u}) \to \dots$ **CC**

Solar fusion $p + p \to {}^2\mathrm{H} + e^+ + \nu_e$ kind of important. . . **CC**

Nuclear β decay e.g. ${}^{60}\mathrm{Co} \to {}^{60}\mathrm{Ni} + e^- + \overline{\nu}_e$ **Wu 1957: P violated** **CC**

Nuclear e^--capture e.g. $e^- + {}^{152}\mathrm{Eu}(J=0) \to {}^{152}\mathrm{Sm}(J=0) + \gamma + \nu_e$ **CC**

Goldhaber 1958: ν helicity measurement

All above mutate quark flavours: individual quark-number violated.

$\nu_l + A \to \nu_l + X$ No charged lepton in final state $\Longrightarrow Z^0$!

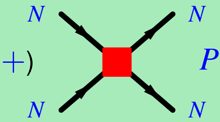
First Neutral-Current (NC) event [CERN 1973; GSW prediction] **NC**

Hadronic Processes (Examples)

Involve only hadrons – window to QCD.

K **decay**	$K^0(d\bar{s}) \to \pi^+(u\bar{d}) + \pi^-(\bar{u}d)$, i.e. $\bar{s} \to \bar{d} + u\bar{u}$	**CC**
$\Lambda(1405)$ **decay**	$\Lambda^0(uds) \to p(uud) + \pi^-(\bar{u}d) \qquad \tau \sim 10^{-10}\ \text{s}$	**CC**

Research Frontier: Hadronic *flavour-conserving* parity-violation (HFCPV), e.g. $pp \to pp$



S-wave (parity $+$)

P-wave (parity $-$)

One of the least-explored sectors of the Standard Model: GW theory: hgrie

- What is the weak part of the nuclear force? (US, EU Long Range Plans)
- Z^0 **(NC) as Inside-Out Probe of non-perturbative QCD:** qq **correlations at** $\dfrac{1}{M_W} \sim 0.002\,\text{fm}$

What we find – and what not (Examples)

Neutral & Charged Current Exchanges with $J^{PC}=1^{--}$, **like for photon**:

Produced as resonances in annihilations and other processes:

$$e^+e^-(\sqrt{s}=90\text{GeV})\to Z^0,\; e^+e^-(\sqrt{s}=160\text{GeV})\to W^+W^-;$$

and in NN or $N\overline{N}$ collisions also resonances from $u\bar{u}\to Z^0$, $u\bar{d}\to W^+$.

$\Longrightarrow$ **Try gauge theory of gauge bosons with charges $\pm 1, 0$?**

Not/Rarely Seen	**Frequently Seen**	**Interpretation**
$\overline{\nu}_e+n\not\to e^-+p$	$\nu_e+n\to e^-+p$	neutrino is not anti-neutrino, $L_e(\nu_e)=-L_e(\overline{\nu}_e)$
$\overline{\nu}_\mu+p\not\to e^++n$	$\overline{\nu}_e+p\to e^++n$	e-neutrino is not μ- neutrino, but. . .
$\nu_\mu+A\not\to e^-+X$	$\nu_\mu+A\to \mu^-+X$	no interactions across lepton families

$\Longrightarrow$ **Natural grouping into lepton families:** $\begin{pmatrix}\nu_e\\ e\end{pmatrix}$, $\begin{pmatrix}\nu_\mu\\ \mu\end{pmatrix}$, $\begin{pmatrix}\nu_\tau\\ \tau\end{pmatrix}$

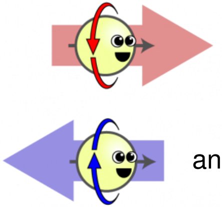
(b) Weak Interactions Violate Parity

Reminder Fermion Helicity & Chirality

[QFT and TCP chapters]

Helicity $h = \dfrac{\vec{\sigma}\cdot\vec{p}}{E}$**:**

spin component longitudinal to $\vec{p}$



parallel: **right-handed** $h = +1$

anti-parallel: **left-handed** $h = -1$

For $m = 0$, indentical to **chirality**: eigenvalues of spinors with respect to γ_5: $\gamma_5\,\varphi_{RL} = \pm\varphi_{RL}$

Projectors: $P_{RL} := \dfrac{1}{2}(1\pm\gamma_5)$, i.e. $P_{RL}\varphi = \varphi_{RL}$, $P_{RL}^2 = P_{RL},\ P_{RL}P_{LR} = 0,\ P_R + P_L = 1$

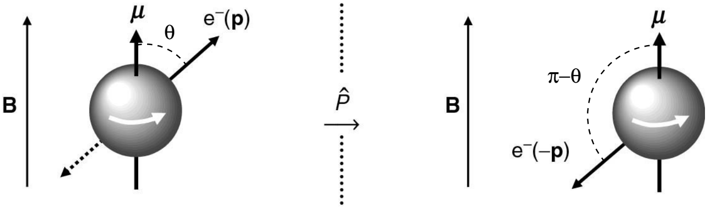
Parity transformation: $\vec{\sigma}$ axial, $\vec{p}$ polar $\Longrightarrow Ph_\pm = h_\mp$

Recall Gauge Theory
Lagrangean in chiral basis: $(\varphi_R^\dagger, \varphi_L^\dagger)\begin{pmatrix} E - gA_0 + \vec{\sigma}\cdot(\vec{p}+g\vec{A}) & m \\ m & E + gA_0 - \vec{\sigma}\cdot(\vec{p}-g\vec{A}) \end{pmatrix}\begin{pmatrix}\varphi_R \\ \varphi_L\end{pmatrix}$

$\Longrightarrow$ **Gauge field does not mix chiralities; only mass term does:** $\propto (1-\beta) = 1 - \dfrac{|\vec{p}|}{E}$.

Electron Helicity from Nuclear β Decay (CC Event)

First: Wu 1957 (prompted by theorists Lee/Yang 1956) $^{60}\mathrm{Co} \to {}^{60}\mathrm{Ni} + e^- + \overline{\nu}_e$



$\vec{B} \widehat{=} \vec{e}_z$ defines quantisation axis

for ^{60}Co spin $\vec{\mu}$ and e^- spin $\vec{\sigma}_e$.

Expectation if parity conserved:

e^- emission uniform $I(\theta) = I(\pi - \theta)$.

Reflection on plane perpendicular to $\vec{\mu}$: $\hat{P}\vec{p} \to -\vec{p}$, $\hat{P}\vec{\mu} \to \vec{\mu}$

Result: Intensity $I(\theta) \neq I(\pi - \theta)$, and emission

of e^- more likely ***against*** ^{60}***Co spin***,

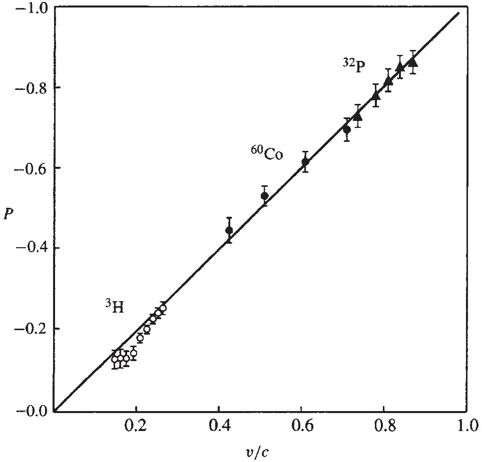
matches dependence on initial e^--polarisation P:

$$I(\theta) = 1 + P\,\frac{\vec{\sigma}_e \cdot \vec{p}_e}{E_e} = 1 + P\,\beta_e \cos\theta$$

and data compatible with $P = -1$.

$\Longrightarrow$ **Parity violated, electron emitted with $h_e = -1$,**

$m_e \neq 0$ explains spin-flip observed in detector.



[Per 7.6 after Koks/van Klinken 1976]

Fig. 7.6. The polarisation P of electrons emitted in nuclear β-decay, plotted as a function of electron velocity. The results demonstrate that $P = -v/c$, as in (7.16). After Koks and Van Klinken (1976).

Similar for $\mu^+ \to e^+ + \nu_e + \overline{\nu}_\mu$: $P(e^+) = +1$.

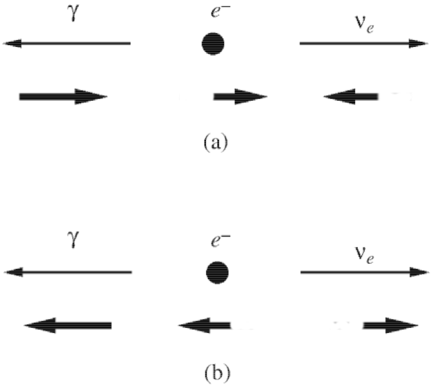
Both confirmed in cornucopia of systems.

Neutrino Helicity from Nuclear Capture (CC event) cf. [PRSZR 18.6, Per 7.6]

First: $e^- + {}^{152}\mathrm{Eu}(J=0) \to {}^{152}\mathrm{Sm}(J=0) + \gamma + \nu_e$ **Goldhaber 1958**

J_z conservation: photon spin ($J=1$) **parallel** to electron spin ($J=\frac{1}{2}$), **antiparallel** to ν spin ($J=\frac{1}{2}$).

$\Longrightarrow$ **Detect photon spin to know ν helicity** (mag. quantum $m_e = m_\gamma + m_\nu$).



$\Longleftarrow$ **found in experiment**

never found in experiment

Figure 6.6 Possible helicities of the photon and neutrinos emitted in the reaction $e^- + {}^{152}\mathrm{Eu}(J=0) \to {}^{152}\mathrm{Sm}(J=0) + \nu_e + \gamma$ for those events in which they are emitted in opposite directions. Experiment selects configuration (a) [Mar]

$\Longrightarrow$ **All evidence suggests: *only* e^-_L, ν_L and e^+_R, $\overline{\nu}_R$ interact weakly in CC events:**

Maximal Parity Violation

(c) Philosophy of the Glashow-Salam-Weinberg Model

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Non-Abelian gauge principle already successful in QCD (QED).

(5) Photon and Z^0 both 1^{--} gauge bosons with no elmag. charge. $\Longrightarrow$ Can mix (Swiss Law).

(6) We still need a massless photon: need a $U(1)_Y$ group somewhere (weak hypercharge).

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$e_R,\nu_{eR},\bar{e}_L,\bar{\nu}_{eL}$ weak (iso-)singlets: $SU(2)_L$ does *not* act on them, but $U(1)_Y$ does.

(8) Same for the other lepton families $\begin{pmatrix}\nu_{\mu L}\\ \mu_L\end{pmatrix},\nu_{\mu R},\mu_R,\begin{pmatrix}\nu_{\tau L}\\ \tau_L\end{pmatrix},\nu_{\tau R},\tau_R$

(c) Philosophy of the Glashow-Salam-Weinberg Model

Universality of weak interactions: simplifies inelegance of 1coupling per $ql\nu$ interaction.

“Theorist’s Theory”: As simple as possible, as flexible as necessary, and compulsory unless forbidden.

First construct sector for one lepton family (e,ν_e):

(1) Start from massless fermions: $\psi_{L/R}$ are eigenstates of γ_5 – generate masses later.

(2) Postulate: only $l_L, \bar{l}_R$ couple to $W^\pm$, but not $l_R, \bar{l}_L$.

(3) $\Longrightarrow$ Right-handed leptons
Left-handed anti-leptons emerge from $W^\pm$ process only after conversion by mass term m_l.

(4) Charged & neutral weak currents mediated by $J^{PC} = 1^{--}$ gauge bosons $W^\pm, Z^0$.

Non-Abelian gauge principle already successful in QCD (QED).

(5) Photon and Z^0 both 1^{--} gauge bosons with no elmag. charge. $\Longrightarrow$ Can mix (Swiss Law).

(6) We still need a massless photon: need a $U(1)_Y$ group somewhere (weak hypercharge).

(7) Lepton-family number conservation:

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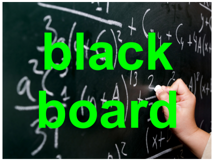
(d) GSW for One Lepton Family

(e) Dynamical Gauge Boson Mass Generation

Nobel 2013

The Higgs-Kibble-Englert Mechanism: A $U(1)$ Example



See Landau-Ginzburg Theory of Superconductivity

A Sketch of Dynamical Mass Generation in GSW

We want 3 massive and 1 massless vector fields, and “true” Higgs filed φ not to couple to photon.

$\Longrightarrow$ Choose complex Higgs doublet $\Phi(x)$, use $SU_L(2)$ gauge trafo to **“Unitary Gauge”**:

$U(x)\Phi(x) = \begin{pmatrix} 0 \\ a + \frac{\varphi(x)}{\sqrt{2}} \end{pmatrix}$ with **real (uncharged) scalar** $\varphi(x)$; cf. weak anti-doublet $\begin{pmatrix} e^+ \\ \overline{\nu}_e \end{pmatrix}$

One Can Show: can always be done: like rotating spin into z direction.

Question: Why is Higgs Vacuum Expectation Value (VEV) $a \neq 0$? — Answer: We do not know.

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One Can Show: can always be done: like rotating spin into z direction.

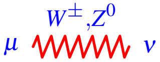
Question: Why is Higgs Vacuum Expectation Value (VEV) $a \neq 0$? — Answer: We do not know.

Determine weak hypercharge such that φ neutral: $0 \overset{!}{=} Q = T_3 + \frac{Y_\varphi}{2} = -\frac{1}{2} + \frac{Y_\varphi}{2}$. $\Longrightarrow Y_\varphi = +1$

$$\Longrightarrow D_\mu\Phi = \left[\partial_\mu \mathbb{1} - \frac{\mathrm{i}}{2}\begin{pmatrix} \overbrace{g\, W^{(3)}_\mu + g'\, B_\mu}^{=\sqrt{g^2+g'^2}A_\mu \text{ photon}} & g\sqrt{2}\, W^+_\mu \\ g\sqrt{2}\, W^-_\mu & \underbrace{-g\, W^{(3)}_\mu + g'\, B_\mu}_{=-\sqrt{g^2+g'^2}Z_\mu} \end{pmatrix}\right]\begin{pmatrix} 0 \\ a + \frac{\varphi(x)}{\sqrt{2}} \end{pmatrix}$$

Multiply out $(D_\mu\Phi)^\dagger(D^\mu\Phi)$: – **massless** photon A_μ

– **masses** $M_W^2 = \frac{g^2 a^2}{2}$, $M_Z^2 = \frac{(g^2+g'^2)\,a^2}{2}$ $\Longrightarrow$

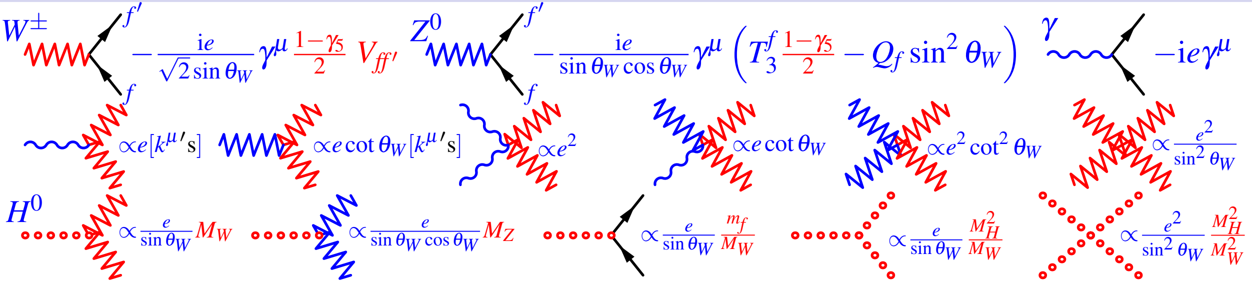


$: \frac{-\mathrm{i}}{q^2 - M^2_{W,Z}}\left[g_{\mu\nu} - \frac{q_\mu q_\nu}{M^2_{W,z}}\right]$

with $\boxed{\frac{M_W^2}{M_Z^2} = \frac{g^2}{g^2+g'^2} = \cos^2\theta_W}$ at “tree level” (before quantum corrections).

(Tree-Level) Interactions and Experimental Numbers

[PDG 2022]
[AH II.Q.2.3]



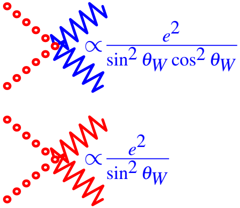
$$-\frac{ie}{\sqrt{2}\sin\theta_W}\gamma^\mu\,\frac{1-\gamma_5}{2}\,V_{ff'}$$

$$-\frac{ie}{\sin\theta_W\cos\theta_W}\gamma^\mu\left(T_3^f\,\frac{1-\gamma_5}{2}-Q_f\sin^2\theta_W\right)$$

$$-ie\gamma^\mu$$

$\propto e[k^\mu{}'\mathrm{s}]$ $\quad\propto e\cot\theta_W[k^\mu{}'\mathrm{s}]$ $\quad\propto e^2$ $\quad\propto e\cot\theta_W$ $\quad\propto e^2\cot^2\theta_W$ $\quad\propto\frac{e^2}{\sin^2\theta_W}$

$\propto\frac{e}{\sin\theta_W}M_W$ $\quad\propto\frac{e}{\sin\theta_W\cos\theta_W}M_Z$ $\quad\propto\frac{e}{\sin\theta_W}\frac{m_f}{M_W}$ $\quad\propto\frac{e}{\sin\theta_W}\frac{M_H^2}{M_W}$ $\quad\propto\frac{e^2}{\sin^2\theta_W}\frac{M_H^2}{M_W^2}$



$\propto\frac{e^2}{\sin^2\theta_W\cos^2\theta_W}$

$\propto\frac{e^2}{\sin^2\theta_W}$

W mass	$M_W=[80.377\pm0.012]\mathrm{GeV}$
Z mass	$M_Z=[91.1876\pm0.0021]\mathrm{GeV}$
Higgs mass	$m_H=[125.25\pm0.17]\mathrm{GeV}$
Weinberg mixing angle	$\sin^2\theta_W(M_Z^2)=0.23121(4)$ ($\theta_W(M_Z^2)\approx29^\circ$)
Fermi coupling	$G_F=1.1663788(6)\times10^{-5}\mathrm{GeV}^{-2}$
Cabbibo angle ($=\lvert V_{us}\rvert/\lvert V_{ud}\rvert$)	$\sin\theta_C=0.2265(5)$ ($\theta_C=13.091(27)^\circ$)

$e\approx g\sin\theta_W\implies\frac{g^2}{4\pi}=\frac{\alpha}{\sin^2\theta_W}\approx\frac{1}{30}\gg\frac{1}{137}=\alpha$ **“Weak Coupling not Weak”**.

Higgs VEV $a\approx\sqrt{2}\,g\,M_W\approx71\ \mathrm{GeV}$

Higgs curvature $\lambda\approx\frac{m_H^2}{4a^2}\approx1.5$ large: narrow valley (wide one would give large corrections).

Has most Nobels: Yang/Lee 1957 (th: P violation), Glashow/Slam/Weinberg 1979 (th: GSW), Cronin 1980 (ex: CP violation), Rubbia/Meer 1984 (ex: W,Z), Ledermannn/Schwartz/Steinberger 1988 (ex: ν_μ), Perl 1995 (ex: τ), Reines 1995 (ex: ν), ’t Hooft/Veltman 1999 (th: QFT of GSW), Davis/Koshiba 2002 (ex: cosmic ν), Kobayashi/Maskawa 2008 (th: CKM), Englert/Higgs 2013 (th: Higgs), Kajita/McDonald 2015 (ex: m_ν).

A Loose End: Fermion Masses by Yukawa Mechanism

So far, no fermion masses: helicity = chirality.

Since Higgs was so good at giving mass to W and Z, let it also generate m_f:

Yukawa Coupling (cf. πN): $\mathcal{L}_{\text{mass}} = \sum\limits_{\substack{\text{all massive} \\ \text{fermions } f}} g_f \left[\bar{f}_L \Phi f_R + \bar{f}_R \Phi^\dagger f_L \right]$ couples L and R chirality

Use $\Phi = \begin{pmatrix} 0 \\ a + \frac{\varphi(x)}{\sqrt{2}} \end{pmatrix}$ $\longrightarrow \sum\limits_f \underbrace{a\, g_f}_{= m_f \text{ fermion mass}} \left[\bar{f}_L f_R + \bar{f}_R f_L \right] +$ fermion-Higgs interactions which **increase** with m_f

Economic but not elegant: one coupling per massive fermion $\Longrightarrow 9\ (12)$ parameters.

Higgs does *not* explain nucleon masses $M_N \approx 940\text{MeV} \gg m_{u,d} \approx 4\text{MeV}$:

Vast majority of hadron mass (and therefore of visible-universe mass)

***comes from QCD*, not from Higgs (contrary to Particle Physicist Propaganda).**

Status of the Higgs Particle 2023

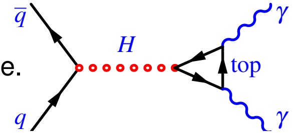
PDG; cf. PRSZR 12.5

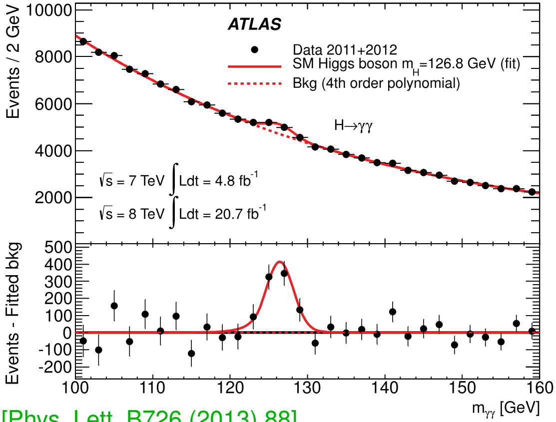
Discovery 2012 at CERN's LHC ($p\bar{p}$ collider): ATLAS & CMS Collaborations.

Discovery channel $q\bar{q} \to H \to \gamma\gamma$:

branching ratio 0.2%, but very clean signature.

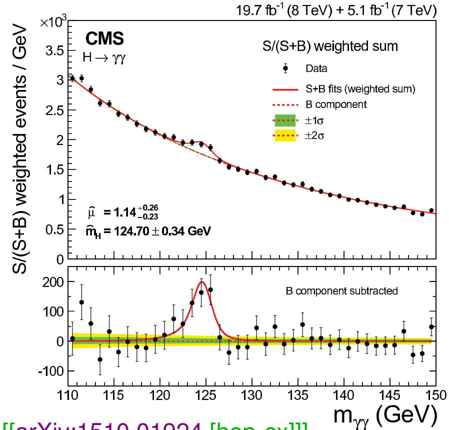
Via "top loop" since tH coupling $\propto m_t$ large.





[Phys. Lett. B726 (2013) 88]

Fig. 2. Invariant mass distribution of diphoton candidates after all selections of the inclusive analysis for the combined 7 TeV and 8 TeV data. The result of a fit to the data with the sum of a SM Higgs boson signal (with $m_H = 126.8$ GeV and free signal strength) and background is superimposed. The residuals of the data with respect to the fitted background are displayed in the lower panel.



[[arXiv:1510.01924 [hep-ex]]]

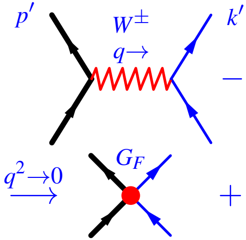
Figure 1: The $m_{\gamma\gamma}$ distribution as weighted sum of all categories [13]. S and B are the number of signal and background events, respectively.

By now, many other channels seen as well. – All results consistent with GSW/Standard Model.

(f) The (Low-Energy) EFT of GSW: Fermi's V-A Theory

$\frac{g^2}{4\pi}\approx\frac{1}{30}\gg\alpha\approx\frac{1}{137}$

$\Longrightarrow$ Why "weak"?



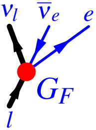
$$-\frac{\mathrm{i}g^2}{2}\left[\overline{U}_L(p')\gamma^\mu U_L(p)\right]\frac{g_{\mu\nu}-\frac{q_\mu q_\nu}{M_W^2}}{q^2-M_W^2}\left[\overline{u}_L(k')\gamma^\nu u_L(k)\right]$$

$$+\frac{g^2}{8M_W^2}\underbrace{\left[\overline{U}\gamma_\mu(1-\gamma_5)U\right]}_{=:\,J_\mu^{\text{weak}}}\left[\overline{u}\gamma^\mu\underbrace{(1-\gamma_5)u}_{=2\overline{u}_L\gamma^\mu U_L}\right]+\mathcal{O}\left(\frac{q^2}{M_W^2}\right)$$

$\Longrightarrow$ For momentum transfers $q^2\ll M_W^2$, see **point-like coupling between Axial Currents** with

Fermi Constant $G_F=\frac{\sqrt{2}\,g^2}{8M_W^2}=1.166\,378\,8(6)\times10^{-5}\mathrm{GeV}^{-2}$ [PDG 2022] $\Longrightarrow$ Postdict M_W!

Example Weak Leptonic Decay $l^-\to e^-\nu_l\overline{\nu}_e$: $\Gamma_l\propto\Big|$



$\Big|^2=\frac{G_F^2m_l^5}{192\pi^3}$ **Sargent's Rule** (dim. an.!)

Prediction $\frac{\Gamma_\tau m_\mu^5}{\Gamma_\mu m_\tau^5}\overset{!}{=}1\Longleftrightarrow$ exp: 0.999 ± 0.003 confirms **Lepton Universality**

Corrections by Taylor & Quantum Effects

suppressed in powers of $\frac{\text{typ. low-momentum}}{\text{breakdown scale}}=\sqrt{\frac{q^2}{M_W^2}}\ll1$

$\Longrightarrow$ limited range of applicability $q^2\ll M_W^2\Longleftrightarrow$ range $\gg\frac{1}{M_W}\approx0.002\mathrm{fm}$ very short-distance!

Fermi's V-A Effective (Low-Energy) Field Theory of GSW

$W^\pm$ couples only to left-handed fermions/right-handed anti-fermions

$\Longrightarrow$ weak microscopic current $J^\mu_{\text{weak}} = \bar{u}_L \gamma^\mu u_L \propto \bar{u}\gamma^\mu (1-\gamma_5) u$: (polar) **V**ector **Minus A**xial (vector)

Fermi's V-minus-A Theory (Model) Fermi 1935 predates GSW by 35 years

Nature Rejection 1933: "contained speculations too remote from reality to be of interest to the reader".

Consequence: Fermi re-evaluates theory career, tries exp. Chicago Reactor. Nobel 1938.

Confinement & Hadronisation shield details of quark→ $W^\pm$ decays inside hadrons. $\Longrightarrow$ V-A modified.

$J^\mu_{\text{weak}} = g_V\, \bar{u}_L \gamma^\mu u_L - g_A\, \bar{u}_L \gamma^\mu \gamma_5 u_L$: couplings g_V, g_A depend on hadron.

$\Longrightarrow$ **Conserved Vector Current CVC** $\bar{u}_L \gamma^\mu u_L$ baryon number must be conserved

Partially Conserved Axial Current PCAC $\bar{u}_L \gamma^\mu \gamma_5 u_L$ not (fully) conserved

PCAC hypothesis (includes Sakurai) predates GSW

Prediction for neutron decay calculation not trivial: $\dfrac{g_A}{g_V} = \dfrac{5}{3} +$ corrections $\Longleftrightarrow 1.2754(13)$ [PDG 2022]

Weak interaction can serve as indirect probe of Physics at $\gtrsim 0.002\text{fm}$:

"Inside-Out Microscope" of QCD & Beyond-Standard-Model

(g) Universality for Quarks

Quark Hypercharges: from $Y_q = 2[Q_q - T_{3q}] \implies$ doublets $\begin{pmatrix} u_L \\ d_L \end{pmatrix}, \begin{pmatrix} c_L \\ s_L \end{pmatrix}, \begin{pmatrix} t_L \\ b_L \end{pmatrix}$ have $Y_{q_L} = +\frac{1}{3}$

$u_R, d_R, c_R, s_R, t_R, b_R$ have $Y_{q_R} = 2Q_q \neq 0 \implies$ quark-equivalents of neutrinos do couple to $U(1)_Y$!

Anti-quarks of opposite helicity have opposite hypercharge.

Quark Decays: $\pi^+(u\bar{d}) \to \pi^0 e^+ \bar{\nu}_e \iff K^+(u\bar{s}) \to \pi^0 e^+ \bar{\nu}_e$

If universal, should differ only by "phase space". $\implies$ Should extract $G^2_{\text{hadr}} \approx 192\pi^3 \frac{\Gamma}{m^5_{\text{hadr}}} \overset{!}{=} G_F^2$!?!

exp: no at all! $G_{\pi^+} \approx 10\; G_{K^+}$ and $G_{\pi^+}, G_{K^+} \neq G_F = 1.16\dots \times 10^{-5}\ \text{GeV}^{-2}$

Postulate common coupling to save quark universality: $G_F \overset{!}{=} \frac{G_{\pi^+}}{\cos\theta_C} \overset{!}{=} \frac{G_{K^+}}{\sin\theta_C}$: **Cabbibo angle θ_C**

exp: The 2 constraints hold. $\sin\theta_C = 0.2265(5)$: $\theta_C = 13.091(27)^\circ$ mnemonic: $\sin^2\theta_W \approx \sin\theta_C$

$\implies$ Leptonic & semi-leptonic weak couplings are related, and we restored & enlarged universality! ✓

Re-definition looks like a rotation of quark/hadron coulings: Change of basis?!?!?!:

$\implies$ **Postulate:** Eigenstates q^{weak} of electro-weak T_3 (coupling to $\gamma W^\pm Z^0$)

are ***not*** eigenstates q^{mass} to mass operator $\hat{M}$ (coupling to Higgs):

$[T_3, \hat{M}] \neq 0$ Not forbidden $\implies$ Compulsory!

Two-Generation Quark Mixing: $(ud), (cs)$ and the GIM Mechanism

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One Can Show: Mathematically, one can *choose* $u_L^{\text{weak}} = u_L^{\text{mass}}$ etc. for upper components of doublet.

Mathematically sufficient to have the *lower* components of the weak doublets mix in flavour space:

$$\begin{pmatrix} d_L^{\text{weak}} \\ s_L^{\text{weak}} \end{pmatrix} = \begin{pmatrix} \cos\theta_C & \sin\theta_C \\ -\sin\theta_C & \cos\theta_C \end{pmatrix} \begin{pmatrix} d_L^{\text{mass}} \\ s_L^{\text{mass}} \end{pmatrix}$$

$\Longrightarrow$ *Weak* eigenstates of doublet couple to $\gamma, W^{\pm}, Z^0$ as before, but *mass* eigentstates mix, e.g.:

Weak Eigenstates
couple via *weak* int.s:

$$W_\mu \bar{u}_L \gamma^\mu d_L^{\text{weak}} = W_\mu \left[\bar{u}_L \gamma^\mu \cos\theta_C \, d_L^{\text{mass}} + \bar{u}_L \gamma^\mu \sin\theta_C \, s_L^{\text{mass}}\right]$$

$$W_\mu \bar{c}_L \gamma^\mu d_L^{\text{weak}} = W_\mu \left[\bar{c}_L \gamma^\mu (-\sin\theta_C) \, d_L^{\text{mass}} + \bar{c}_L \gamma^\mu \cos\theta_C \, s_L^{\text{mass}}\right]$$

Consequence of Dictate of Universality: Works only if one weak-isospin partner for *each* quark!

$\Longrightarrow$ New 4th quark *must* complete 2nd-generation doublet $\begin{pmatrix} \otimes_L \\ s_L \end{pmatrix}$ [Glashow/Iliopulos/Maiani (GIM) 1970]
[followed by $J/\psi(c\bar{c})$ discovery 1973]

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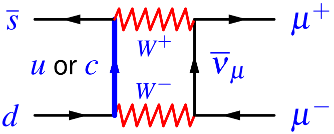
GIM Mechanism: flavour-changing neutral currents suppressed, e.g. $K^0(d\bar{s}) \to W^+W^- \to \mu^+\mu^-$:



$$d \xrightarrow{\cos\theta_C} u \xrightarrow{\sin\theta_C} s$$

$$d \xrightarrow{-\sin\theta_C} c \xrightarrow{\cos\theta_C} s$$

Equal in magnitude, opposite in sign.

$\Longrightarrow$ Amplitudes cancel!

tiny nonzero because $m_u \neq m_c$

(h) Mixing for Three Generations: One Can Show

– Most general form allows upper entries of weak doublet to be eigenstates to *both* mass *and* weak:

$$u_w = u_m \qquad c_w = c_m \qquad t_w = t_m$$

– Most general matrix which mixes lower entries:

$$\underbrace{\begin{pmatrix} d_w \\ s_w \\ b_w \end{pmatrix}}_{\text{weak eigenstates}} = \underbrace{\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}}_{\text{Cabibbo-Kobayashi-Maskawa (CKM) matrix – includes Cabibbo matrix}} \underbrace{\begin{pmatrix} d_m \\ s_m \\ b_m \end{pmatrix}}_{\text{mass eigenstates}}$$

W/oLOG parametrised by 3 magnitudes $+$ **1 complex phase: CP-violation in $K^0/\overline{K}^0$ ($\delta \approx 70^\circ$):**

$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{pmatrix} = \begin{pmatrix} 0.97401(11) & 0.22650(48) & 0.00361^{(11)}_{(9)} \\ 0.22636(48) & 0.97320(11) & 0.04053^{(9)}_{(83)} \\ 0.00854^{(23)}_{(16)} & 0.03978^{(82)}_{(60)} & 0.999172^{(24)}_{(35)} \end{pmatrix}$$

From weak decays of N, K, B, D,...

[PDG 2022]

– **Experiment:** Diagonal elements: coupling within same generation: ≈ 1

– **Experiment:** Off-diagonal elements much smaller:

mixing generations $1 \longleftrightarrow 2$: ≈ 0.2

mixing generations $2 \longleftrightarrow 3$: $\approx 0.04 = 0.2^2$

mixing generations $1 \longleftrightarrow 3$: $\approx 0.008 = 0.2^3$

Why that hierarchy?

Unitarity Test of the CKM matrix: Measure all matrix entries (including 3 complex phases).

– So far unitary $\Longrightarrow$ really 3 generations. If not: **New Quark Family/Beyond-Standard-Model??**

What About Mixing Leptons?

Kajita(SuperKamiokande)+McDonald(SNO)
Nobel 2015 for detection

Assumed massless neutrinos. $\Longrightarrow$ No difference between mass and weak eigenstates.

But why should neutrinos be massless? – No compelling symmetry found.

Swiss Basic Law: Everything which is not forbidden, is compulsory.

Neutrino oscillations seen in solar, atmospheric, reactor & collider neutrino experiments: $m_\nu \sim \mathrm{eV}$'ish

$\Longrightarrow$ Introduce analogue to CKM matrix, but now for *upper entries* of weak doublet (convenience).

$$\underbrace{\begin{pmatrix} \nu_{ew} \\ \nu_{\mu w} \\ \nu_{\tau w} \end{pmatrix}}_{\text{weak eigenstates}} = \underbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}}_{\text{Pontecorvo-Maki-Nakagawa-Sakata}} \underbrace{\begin{pmatrix} \nu_{1m} \\ \nu_{2m} \\ \nu_{3m} \end{pmatrix}}_{\text{mass eigenstates}}$$

Pontecorvo-Maki-Nakagawa-Sakata
(PMNS) matrix: unitary, indep. parameters:
3 real & 1 CP-violating phase $\delta = 245(32)^\circ$

Much less diagonal that CKM (plus one complex phase, at present undetermined): [PDG2022]

$$\begin{pmatrix} |U_{e1}| & |U_{e2}| & |U_{e3}| \\ |U_{\mu 1}| & |U_{\mu 2}| & |U_{\mu 3}| \\ |U_{\tau 1}| & |U_{\tau 2}| & |U_{\tau 3}| \end{pmatrix} = \begin{pmatrix} 0.82 & 0.55 & 0.15 \\ 0.36 & 0.70 & 0.61 \\ 0.44 & 0.46 & 0.77 \end{pmatrix}$$ — with errors $\pm[0.01 \ldots 0.06]$

Neutrino Oscillations: 2×2 Case as 2-State QM [PRSZR 11, PDG 10/14]

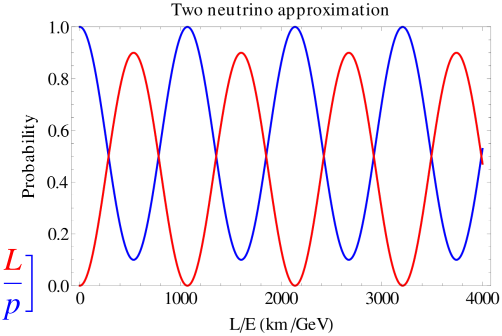
$$\begin{pmatrix}\nu_{ew}\\ \nu_{\mu w}\end{pmatrix}=\begin{pmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}\nu_{1m}\\ \nu_{2m}\end{pmatrix}\implies$$ time-evolution when only 1 species produced at $t=0$:

$$|\nu_{ew}(t)\rangle=\cos\theta\,\mathrm{e}^{-\mathrm{i}E_{\nu 1}t}|\nu_{1m}\rangle+\sin\theta\,\mathrm{e}^{-\mathrm{i}E_{\nu 2}t}|\nu_{2m}\rangle$$

Ultra-relativistic: $E_\nu=\sqrt{p^2+m_\nu^2}\overset{E\gg m}{\approx}p\left(1+\dfrac{m_\nu^2}{2p^2}\right)$

$\implies$ Probability to find $|\nu_{ew}(t)\rangle$ at $L=\beta t=t$:

$$|\langle\nu_{ew}(L)|\nu_{ew}(0)\rangle|^2=1-\sin^2 2\theta\,\sin^2\left[\frac{\Delta m_{12}^2=(m_1^2-m_2^2)}{4}\,\frac{L}{p}\right]$$



Disappearance Experiment: find remaining original ↔ **Appearance Experiment:** look for converted.

$\Delta m^2\ll\mathrm{eV}^2,\ p\gtrsim\mathrm{MeV}\implies L\gg\dfrac{\mathrm{MeV}}{\mathrm{eV}^2}\sim\mathrm{km}$: **QM interference on macroscopic lengths.**

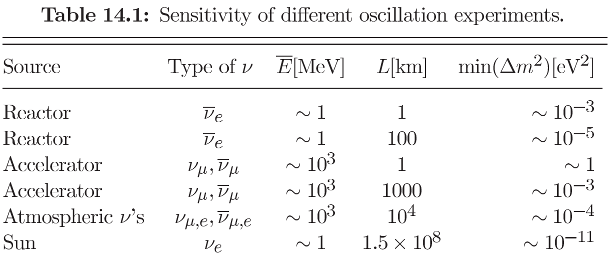


Table 14.1: Sensitivity of different oscillation experiments.

Source	Type of ν	$\overline{E}$[MeV]	L[km]	min(Δm^2)[eV^2]
Reactor	$\overline{\nu}_e$	~ 1	1	$\sim 10^{-3}$
Reactor	$\overline{\nu}_e$	~ 1	100	$\sim 10^{-5}$
Accelerator	$\nu_\mu,\overline{\nu}_\mu$	$\sim 10^3$	1	~ 1
Accelerator	$\nu_\mu,\overline{\nu}_\mu$	$\sim 10^3$	1000	$\sim 10^{-3}$
Atmospheric ν's	$\nu_{\mu,e},\overline{\nu}_{\mu,e}$	$\sim 10^3$	10^4	$\sim 10^{-4}$
Sun	ν_e	~ 1	1.5×10^8	$\sim 10^{-11}$

[PDG 2015]

Besides θ, combination $\dfrac{\Delta m^2\,L}{p=E}$ gives sensitivity:

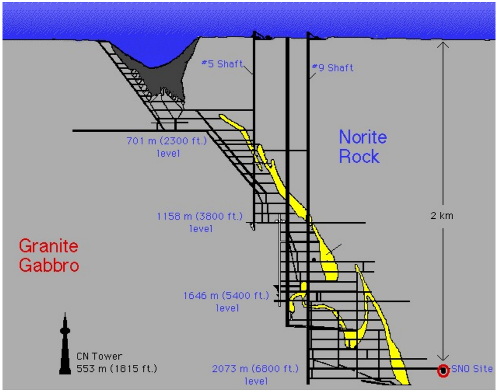
Reactor: ⊕ short L, controlled ⊖ low-E

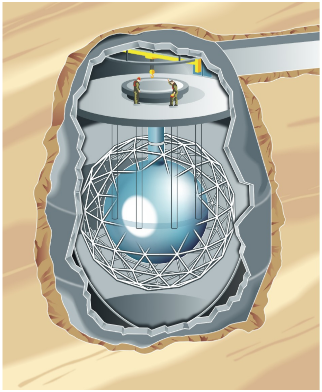
Accelerator: ⊕ high-E, controlled ⊖ short L

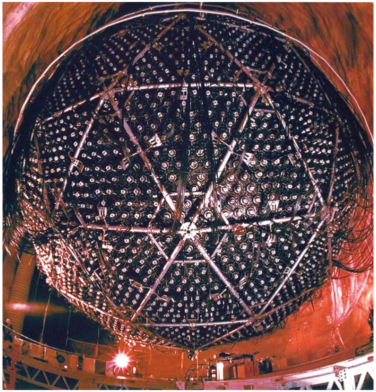
Atmospheric: ⊕ high-E, $L=R_{\mathrm{Earth}}$ ⊖ no control

Solar: ⊕ longest baseline ⊖ solar modelling

Sudbury Neutrino Observatory SNO: Test Solar Neutrinos



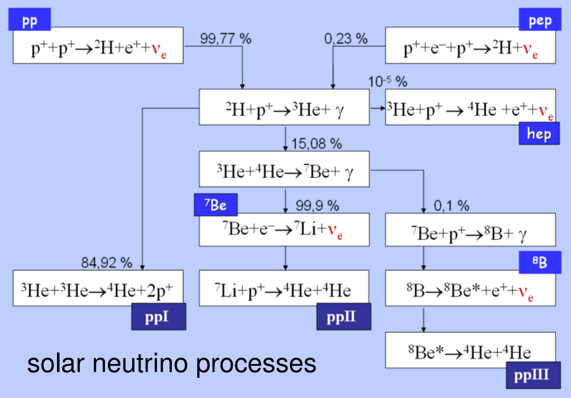




$1,000\mathrm{m}^3$ $\mathrm{D_2O}$, monitored by $9,600$ Photomultipliers for Čerenkov light

$2\mathrm{km}$ under ground in operating nickel mine in Sudbury, Ontario, Canada.

SNO: Comprehensive Measurement of Neutrino Flux



pp

$p^+ + p^+ \to {}^2H + e^+ + \nu_e$

99,77 %

pep

$p^+ + e^- + p^+ \to {}^2H + \nu_e$

0,23 %

$^2H + p^+ \to {}^3He + \gamma$

10-5 %

$^3He + p^+ \to {}^4He + e^+ + \nu_e$

hep

15,08 %

$^3He + {}^4He \to {}^7Be + \gamma$

7Be

99,9 %

$^7Be + e^- \to {}^7Li + \nu_e$

0,1 %

$^7Be + p^+ \to {}^8B + \gamma$

8B

84,92 %

$^3He + {}^3He \to {}^4He + 2p^+$

ppI

$^7Li + p^+ \to {}^4He + {}^4He$

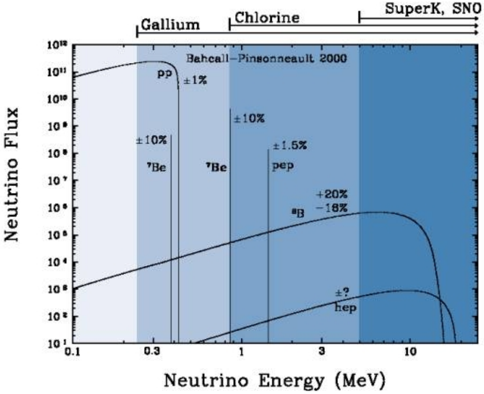
ppII

$^8B \to {}^8Be^* + e^+ + \nu_e$

$^8Be^* \to {}^4He + {}^4He$

ppIII

solar neutrino processes



Measure **total *and* individual solar neutrino flux**

by Čerenkov of superluminal e^- of different origins:

Φ_e via $\nu_e d \to ppe^-$: breakup, omnidirectional: **CC**

$\Phi_e + \Phi_{\mu\tau}$ via $\nu_{e\mu\tau} d \to pn\nu_{e\mu\tau}$: inel. scatt. **NC**

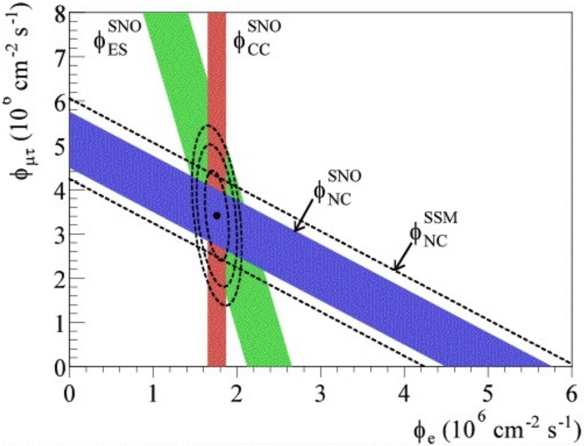
$nd \to {}^3\mathrm{H}\gamma(6\mathrm{MeV})$, $\gamma e^- \Rightarrow e^-$ superlum.

$\Phi_e + 0.16\Phi_{\mu\tau}$ via $\nu_{e\mu\tau} e^- \to \nu_{e\mu\tau} e^-$: forward **ES**

Agrees excellently with Standard Solar Model!

$\Phi({}^8\mathrm{B}) \propto \mathrm{Temp}_{\mathrm{Sun}}^{25} \leftrightarrow T_{\mathrm{Sun}} = 15.7 \times 10^6\mathrm{K} \pm 1\%$.

$\theta_{12} = 33.6(8)^\circ$, $\Delta m_{12}^2 = 7.53(0.18) \times 10^{-5}\mathrm{eV}^2$



Neutrino Oscillations: What We Know, What Not, and What's Cool

– Weak and mass eigenstates of neutrinos different. $\Longrightarrow$ Neutrinos mix.

– Neutrinos have nonzero mass-difference, ν_e is lightest.

– Is lightest neutrino massless? – What are the individual masses?

– Is $m_{\nu\mu} < m_{\nu\tau}$ (ordered like quark & charged-lepton masses), or $m_{\nu\mu} > m_{\nu\tau}$ ("inverted ordering")?

Majorana Neutrinos? So far, $\nu = \begin{pmatrix} \text{particle}_R \\ \text{particle}_L \\ \text{antiparticle}_R \\ \text{antiparticle}_L \end{pmatrix}$ was **Dirac spinor**, but only ν_L and $\overline{\nu}_R$ couple.

Neutrinos charge-neutral, weak hypercharge is $Y = 0$.

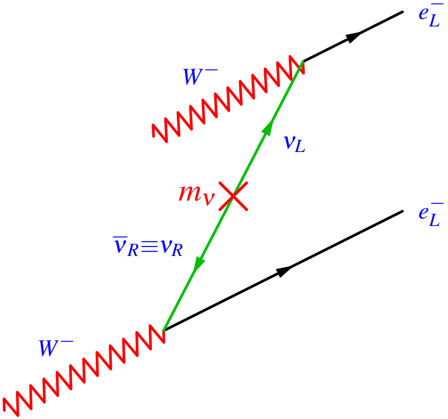
$\Longrightarrow$ **Could be its own antiparticle:** $\nu_R \equiv \overline{\nu}_R$, $\nu_L \equiv \overline{\nu}_L$

If so, then use that nonzero masses mix helicities e.g. in

$W^- \to e^- + (\overline{\nu}_R \equiv \nu_R)$: W^- decay

mass converts helicity: $\nu_R \xrightarrow{m_\nu \neq 0} \nu_R + \dfrac{m_\nu}{p_\nu}\, \nu_L$, $\dfrac{m_\nu}{p_\nu} \ll 1$

e^- production $\nu_L + W^- \to e^-$



$\Longrightarrow$ **Lepton Number violated by 2 units, probability $\propto \dfrac{m_\nu^2}{p_\nu^2}$!**

(i) Summarising Some Features of the GSW Theory

What We Like and Dislike About the GSW Theory

- 3 generations of quarks and leptons: nicely symmetric.

$$\begin{pmatrix}\nu_{eL}\\ e_L\end{pmatrix}\begin{pmatrix}\nu_{\mu L}\\ \mu_L\end{pmatrix}\begin{pmatrix}\nu_{\tau L}\\ \tau_L\end{pmatrix}\quad\begin{pmatrix}u_L\\ d_L\end{pmatrix}\begin{pmatrix}c_L\\ s_L\end{pmatrix}\begin{pmatrix}t_L\\ b_L\end{pmatrix}\qquad l_R\;q_R$$

- Every particle but photon gets a mass: **Higgs-Kibble-Englert and Yukawa mechanisms**.
- **Unified** electromagnetic and weak interaction: 2 sides of same coin: first unification since Maxwell.
- **Universality** for *all* fermions.
- Has not failed any test yet – and we are really talking precision!
- But it took advantage of all freedoms ($W^0_\mu\, B_\mu$ mixing, weak eigenstates, ν mass,. . .)
- And why is parity violated in the first place?
- **Not nice:** not *one* coupling, but *two*: $g,\, g'$ (or $e,\, \theta_W$)

  plus 2 Higgs parameters: VEV a & curvature λ,

  plus 2×4 CKM/PMNS mixing parameters,

  plus 2×6 Higgs-fermion couplings to generate lepton & quark masses:

  24 parameters is a lot!

  QCD: 1 ($\alpha_s(M_Z^2)\longleftrightarrow\Lambda_{QCD}$) & 6 (double-counted) quark masses & 1 “vacuum angle” θ_{QCD}
- **Not nice:** Higgs the only “fundamental” scalar field in Nature – and why is its VEV nonzero??

(j) QCD vs. GSW

Both are **Quantum Field Theories**, and even **Gauge Theories**, and even **non-Abelian**.

$\Longrightarrow$ Both show asymptotic freedom as $q^2 \to \infty$.

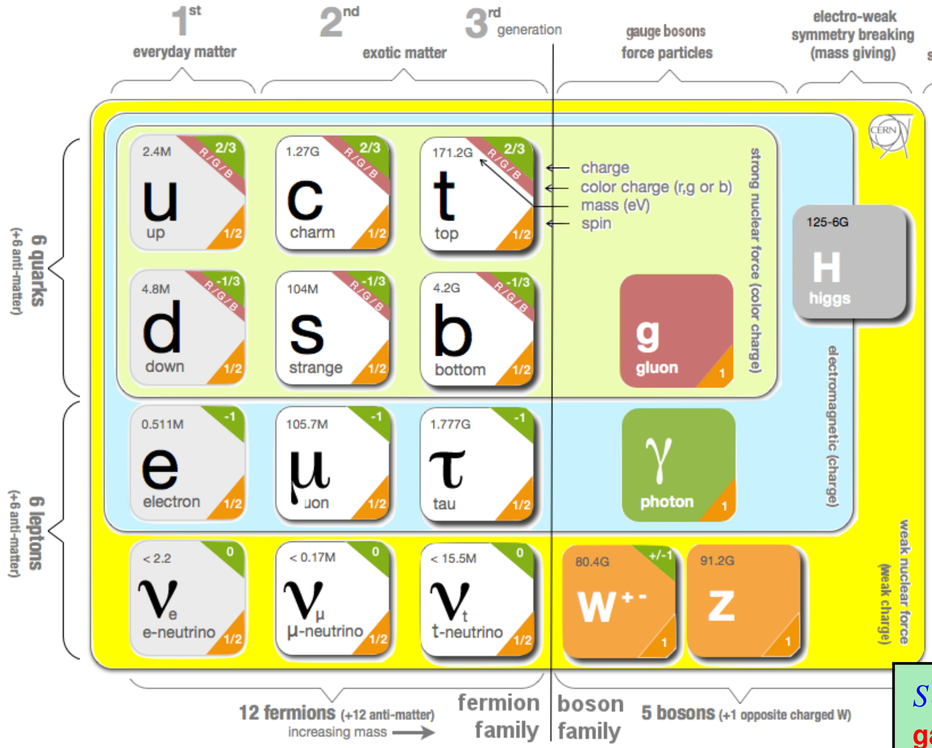
Obvious differences: only quark-gluon via colour $SU_c(3)$ vs. all particles via $SU_L(2) \times U_Y(1)$.

There are some oft-overlooked *fundamental* differences:

QCD (Confinement Phase)	**GSW (Higgs Phase)**
q & g confinement: not in detector	single leptons and gauge particles $\gamma, W^{\pm}, Z^0$ observed in detector
absence of coloured states	states with nonzero charge Q, hypercharge Y, weak isospin $\vec{T}$ are common $(e, \tau, \mu, \nu, \dots)$
nonperturbative at $q^2 \lesssim (3\,\mathrm{GeV})^2$	perturbative everywhere
low-energy complicated: lattice, χEFT	$q^2 \lesssim (30\,\mathrm{GeV})^2$: EFT is simple Fermi/V-A
gluons massless (at least in perturbative régime)	3 of 4 gauge bosons massive by Higgs mechanism

It's fair to say we do not understand why these are so different.

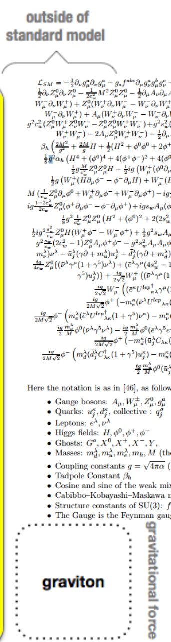
6. Finally: The Standard Model – and Beyond



$$
\begin{gathered}
\mathcal{L}_{SM} = -\frac12\partial_\nu g^a_\mu\partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac14 g_s^2 f^{abc}f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu - \partial_\nu W^+_\mu\partial_\nu W^-_\mu - M^2 W^+_\mu W^-_\mu - \\
\frac12\partial_\nu Z^0_\mu\partial_\nu Z^0_\mu - \frac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \frac12\partial_\mu A_\nu\partial_\mu A_\nu - igc_w(\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - \\
W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)) - igs_w(\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu\partial_\nu W^-_\mu - \\
W^-_\mu\partial_\nu W^+_\mu) + A_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)) - \frac12 g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \frac12 g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + \\
g^2c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w(A_\mu Z^0_\nu(W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu) - \frac12\partial_\mu H\partial_\mu H - 2M^2\alpha_h H^2 - \partial_\mu\phi^+\partial_\mu\phi^- - \frac12\partial_\mu\phi^0\partial_\mu\phi^0 - \\
\beta_h\left(\frac{2M^2}{g^2} + \frac{2M}{g}H + \frac12(H^2+\phi^0\phi^0+2\phi^+\phi^-)\right) + \frac{2M^4}{g^2}\alpha_h - g\alpha_h M\left(H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-\right) - \\
\frac18 g^2\alpha_h\left(H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2\right) - gMW^+_\mu W^-_\mu H - \\
\frac12 g\frac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \frac12 ig\left(W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)\right) + \\
\frac12 g\left(W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) + W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)\right) + \frac12 g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) + \\
M\,(\frac{1}{c_w}Z^0_\mu\partial_\mu\phi^0 + W^+_\mu\partial_\mu\phi^- + W^-_\mu\partial_\mu\phi^+) - ig\frac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_wMA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - \\
ig\frac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_wA_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \frac14 g^2W^+_\mu W^-_\mu\left(H^2+(\phi^0)^2+2\phi^+\phi^-\right) - \\
\frac18 g^2\frac{1}{c_w^2}Z^0_\mu Z^0_\mu\left(H^2+(\phi^0)^2+2(2s_w^2-1)^2\phi^+\phi^-\right) - \frac12 g^2\frac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) - \\
\frac12 ig^2\frac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac12 g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) + \frac12 ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - \\
g^2\frac{s_w}{c_w}(2c_w^2-1)Z^0_\mu A_\mu\phi^+\phi^- - g^2s_w^2A_\mu A_\mu\phi^+\phi^- + \frac12 ig_s\,\lambda^a_{ij}(\bar q^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu - \bar e^\lambda(\gamma\partial + m^\lambda_e)e^\lambda - \bar\nu^\lambda(\gamma\partial + \\
m^\lambda_\nu)\nu^\lambda - \bar u^\lambda_j(\gamma\partial + m^\lambda_u)u^\lambda_j - \bar d^\lambda_j(\gamma\partial + m^\lambda_d)d^\lambda_j + igs_wA_\mu\left(-(\bar e^\lambda\gamma^\mu e^\lambda) + \frac23(\bar u^\lambda_j\gamma^\mu u^\lambda_j) - \frac13(\bar d^\lambda_j\gamma^\mu d^\lambda_j)\right) + \\
\frac{ig}{4c_w}Z^0_\mu\{(\bar\nu^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar e^\lambda\gamma^\mu(4s_w^2-1-\gamma^5)e^\lambda) + (\bar d^\lambda_j\gamma^\mu(\frac43 s_w^2-1-\gamma^5)d^\lambda_j) + (\bar u^\lambda_j\gamma^\mu(1-\frac83 s_w^2 + \\
\gamma^5)u^\lambda_j)\} + \frac{ig}{2\sqrt2}W^+_\mu\left((\bar\nu^\lambda\gamma^\mu(1+\gamma^5)U^{lep}{}_{\lambda\kappa}e^\kappa) + (\bar u^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)\right) + \\
\frac{ig}{2\sqrt2}W^-_\mu\left((\bar e^\kappa U^{lep\dagger}{}_{\kappa\lambda}\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar d^\kappa_j C^\dagger_{\kappa\lambda}\gamma^\mu(1+\gamma^5)u^\lambda_j)\right) + \\
\frac{ig}{2M\sqrt2}\phi^+\left(-m^\kappa_e(\bar\nu^\lambda U^{lep}{}_{\lambda\kappa}(1-\gamma^5)e^\kappa) + m^\lambda_\nu(\bar\nu^\lambda U^{lep}{}_{\lambda\kappa}(1+\gamma^5)e^\kappa\right) + \\
\frac{ig}{2M\sqrt2}\phi^-\left(m^\lambda_e(\bar e^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1+\gamma^5)\nu^\kappa) - m^\kappa_\nu(\bar e^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1-\gamma^5)\nu^\kappa)\right) - \frac g2\frac{m^\lambda_\nu}{M}H(\bar\nu^\lambda\nu^\lambda) - \frac g2\frac{m^\lambda_e}{M}H(\bar e^\lambda e^\lambda) + \\
\frac{ig}{2}\frac{m^\lambda_\nu}{M}\phi^0(\bar\nu^\lambda\gamma^5\nu^\lambda) - \frac{ig}{2}\frac{m^\lambda_e}{M}\phi^0(\bar e^\lambda\gamma^5 e^\lambda) - \frac14\bar\nu_\lambda\,M^R_{\lambda\kappa}\,(1-\gamma_5)\hat\nu_\kappa - \frac14\overline{\bar\nu_\lambda\,M^R_{\lambda\kappa}\,(1-\gamma_5)\hat\nu_\kappa} + \\
\frac{ig}{2M\sqrt2}\phi^+\left(-m^\kappa_d(\bar u^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m^\lambda_u(\bar u^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j\right) + \\
\frac{ig}{2M\sqrt2}\phi^-\left(m^\lambda_d(\bar d^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m^\kappa_u(\bar d^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j)\right) - \frac g2\frac{m^\lambda_u}{M}H(\bar u^\lambda_j u^\lambda_j) - \frac g2\frac{m^\lambda_d}{M}H(\bar d^\lambda_j d^\lambda_j) + \\
\frac{ig}{2}\frac{m^\lambda_u}{M}\phi^0(\bar u^\lambda_j\gamma^5 u^\lambda_j) - \frac{ig}{2}\frac{m^\lambda_d}{M}\phi^0(\bar d^\lambda_j\gamma^5 d^\lambda_j)
\end{gathered}
$$

Here the notation is as in [46], as follows.

- Gauge bosons: $A_\mu, W^\pm_\mu, Z^0_\mu, g^a_\mu$
- Quarks: u^κ_j, d^κ_j, collective : q^σ_j
- Leptons: e^λ, ν^λ
- Higgs fields: $H, \phi^0, \phi^+, \phi^-$
- Ghosts: $G^a, X^0, X^+, X^-, Y,$
- Masses: $m^\lambda_d, m^\lambda_u, m^\lambda_e, m_h, M$ (the latter is the mass of the W)
- Coupling constants $g = \sqrt{4\pi\alpha}$ (fine structure), g_s = strong, $\alpha_h = \frac{m_h^2}{4M^2}$
- Tadpole Constant β_h
- Cosine and sine of the weak mixing angle c_w, s_w
- Cabibbo–Kobayashi–Maskawa mixing matrix: $C_{\lambda\kappa}$
- Structure constants of SU(3): f^{abc}
- The Gauge is the Feynman gauge.

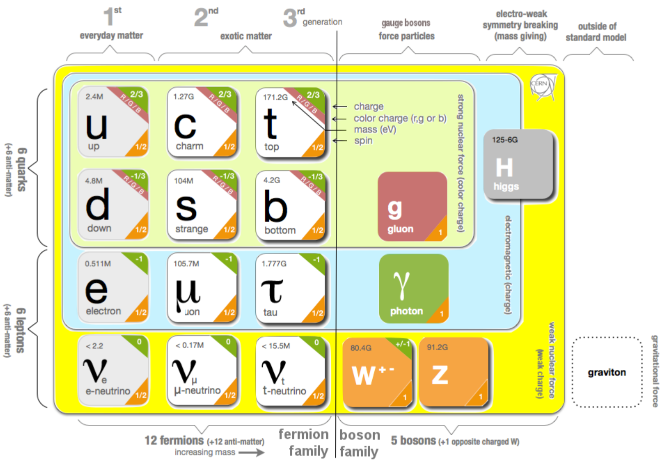


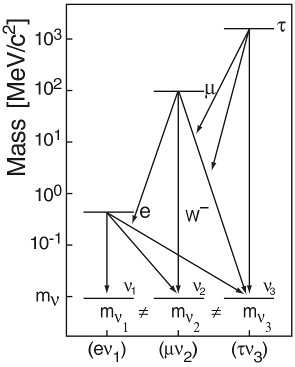
$SU_c(3) \times SU_L(2) \times U_Y(1)$

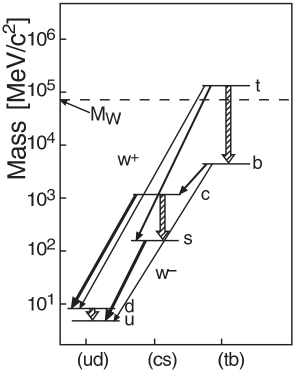
gauge theory

This was a great time [. . .], the period of the famous triumph of quantum field theory. And what a triumph it was, in the old sense of the word: a glorious victory parade, full of wonderful things brought back from far places to make the spectator gasp with awe and laugh with joy. [S. Coleman 1985]

Answered a Lot of Questions, but Leave Many Open, For Example:







– Unification to 1 parameter

– Mass hierarchy problem

– Gravitation not quantised

– Why 3 generations?

– Why $Q = \pm 1, \pm\frac{2}{3}, \pm\frac{1}{3}, 0$?

– Why these gauge groups?

– Why 4 dimensions?

$\Longrightarrow$ **Simplify (fewer parameters), or find processes which are not explained by freedoms of SM!**

Look for new fundamental particles (supersymmetry, strings, prions) & forces (dark energy/matter), violations of lepton & baryon number & universalities, Lorentz invariance,. . .

Lots of answers, but each raises more questions! $\Longrightarrow$ **Your Turn!**

But Wait, There is *More*: in PHYS 6710:

Nuclear and Particle Physics II:

THE RETURN OF THE THEORIST

Topics Tuned To Audience; Typically: **Less-Informal QFT & Renormalisation – Less-Informal Statistics & Data Analysis – Instrumentation**

Spring 2024 – watch this space!