g_c is a free, unknown coupling constant
In the literature, one finds that a typical convention is $\frac{g_c^2}{4\pi} = 1$

$\eta_{LR} = \eta_{RL}$

$\Lambda = \Lambda_{LL}^{\pm}$ for $(\eta_{LL}, \eta_{RR}, \eta_{LR}) = (\pm 1, 0, 0)$

$\Lambda_{RR}^{\pm}$ $(0, \pm 1, 0)$

$\Lambda_{VV}^{\pm}$ $(\pm 1, \pm 1, \pm 1)$

$\Lambda_{AA}^{\pm}$ $(\pm 1, \pm 1, \mp 1)$

$\Lambda_{V-A}^{\pm}$ $(0, 0, \pm 1)$

Contact interaction scattering amplitudes can interfere with SM amplitudes destructively or constructively
e.g. $qq \to qq$ in $\Lambda_{LL}^{\pm}$ model $\eta_{LL} = +1$ destructive
$\eta_{LL} = -1$ constructive

Excited quarks (and leptons) can appear in various SU(2) doublets

sequential: $\begin{pmatrix} u^* \\ d^* \end{pmatrix}_L$ u_R^* d_R^*

mirror: u_L^* d_L^* $\begin{pmatrix} u^* \\ d^* \end{pmatrix}_R$

homodoublet: $\begin{pmatrix} u^* \\ d^* \end{pmatrix}_L$ $\begin{pmatrix} u^* \\ d^* \end{pmatrix}_R$

Production: either - via gauge interactions
- via contact interactions with SM leptons/quarks

Decay: $q^* \to q g$
$q \gamma$
$q' W,\ q Z$

→ look for resonances dijet, jet+photon, jet+W/Z

Alternatively: in the tail of the jet p_T spectrum

Or: in angular distribution
define y_1 and y_2 as rapidity of highest p_T jets

$$\chi = e^{|(y_1 - y_2)|} = \frac{1 + |\cos\theta^*|}{1 - |\cos\theta^*|}$$

with θ^* scattering angle in partonic center of mass
QCD: χ distribution flat (approximately)
excited quarks: low χ
or contact interactions

Excited leptons: $\ell^* \to \ell \gamma$
ℓZ (3-lepton final states)
$\nu^* \to \ell W$

In the theme of additions to the SM matter particles, let's look at a few more "exotic" candidates.

▷ Free quarks
Or more generally: "isolatable fractionally charged particles
↙
free, or attached to a nucleus
$Q_{tot} \neq$ integer
Quarks are special case $Q = \pm 2/3,\ \pm 1/3$

By the way: quark charge $\pm 1/3$, $\pm 2/3$ established by interactions with photons

cross section $\sim Q^2$

(Alternative quark model with integer charges does not work)

(Also: $Q_{top} = 5/3$ ruled out by looking at correlation of charge of W and b in $t \to Wb$)

Searching for fractionally charged particles:

make use of characteristic ionization: $\frac{dE}{dx} \sim Q^2$

LEP: $e^+e^- \to F^{x+} F^{x-}$ rules out $M_F < 100$ GeV for $x \geq$

Very difficult to go lower in x

$\downarrow$

clean environment

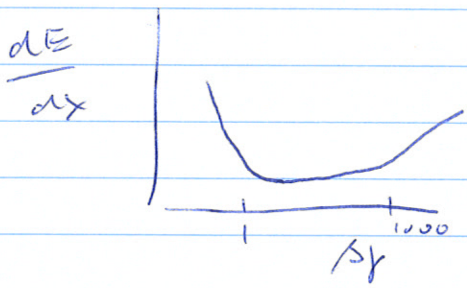
Hadron colliders: $p\bar{p} \to F^{x+} F^{x-}$ @ CDF

$pp \to F^{x\pm} + X$ @ CMS

Very busy environment, not easy

One "trick": look for high masses, $m \sim E \Rightarrow$ small $p \to$ low

At low β, we are at the low end of the Bethe-Bloch



$\Rightarrow$ easier to look for anomalously high ionization than low ionization

Other searches for fractionally charged particles:

- nuclear collisions — nuclear fragments with non-integer charge

- cosmic rays $\Rightarrow$ airshowers

  penetrating particles: underground detectors
  (but loose ability to detect strongly interacting part. like quarks)

- bulk matter: oil drop experiment a la Millikan
  vs in an oscillating E field
  or magnetic suspension ("levitometer")

- in meteorites (best chance of survival from production in early universe)

▷ Multi-charged particles

ATLAS: long-lived charged particles $q = 2-6\ e$
look like muons, but with anomalous dE/dx

also ATLAS: particles with anomalous ionization,
stopping in the calorimeter $q = 20-60\ e$

Special case of such a particle: Dirac monopole

Dirac: symmetrize Maxwell equations
$\Rightarrow$ magnetic monopole with magnetic charge g

only consistent equations in quantum mechanics if

$$e \cdot g = \frac{1}{2} n \hbar c$$

$$n = 1: \quad \frac{g}{e} = \frac{1}{2\alpha} \approx 68.5$$

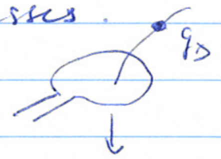
In terms of ionization properties; a Dirac monopole behaves like a charged particle with $q = 68.5\,e$

ATLAS search : mass limits ~ 1 TeV

(but production cross section uncertain)

Monopoles also arise in GUT theories with cosmological consequences, but with GUT-scale masses.

Searches for magnetic properties: SQUIDs



*

> Heavy stable charged particles

$\tau > \frac{30 \text{ meter}}{c}$ look like stable (like muon

normally $q = 1$ (stable supersymmetric particles)

very muon-like, unless high $m \rightarrow$ low $p \rightarrow$ low,

use dE/dx and timing (time-of-flight)

> Stable, stopping particles

Some categories of particles could have long lifetimes

(long compared to LHC bunch crossing frequency : > 100

and stop in material, and decay much later

(anything from μs to years)

ATLAS and CMS search for particles decaying in their calorimeters, leading to jets, when there are no pp colli

(However: cosmic ray background)

* (more monopole searches: MoEDAL @ LHC nuclear tracking d

Antares

▷ Leptoquarks

Hypothetical particles carrying both lepton- and baryonnumber

Spin 0 : Scalar LQ   spin 1 : Vector LQ

Assumed to couple to SM gauge bosons

SU(3) triplet   SU(2) either singlet, doublet or triplet

LQ would typically decay to lepton + quark.

If LQ coupling transcends generations: flavour-changing neutral cur

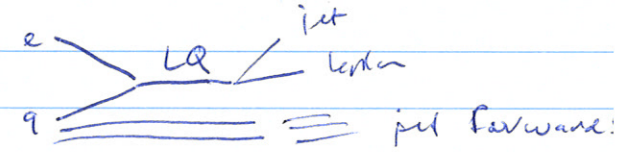
No observation of FCNC : 1^{st}, 2^{nd}, 3^{rd} generation LQ

couplings stay within generation

Searches : $q + \bar{q} \rightarrow LQ + \overline{LQ}$

$g + g \rightarrow LQ + \overline{LQ}$

$e + q \rightarrow LQ$ HERA!



"Exotic" but really Standard Model:

glue balls

pentaquarks

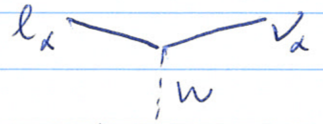
"strange" matter in neutron stars

Neutrino's

Weak interactions of neutrino's: $W \left(\begin{matrix} \nu \\ e \end{matrix} \right)_L W$

define the <u>flavour</u> eigenstates of neutrino's.

Interactions with W always involve a specific flavour of charged lepton, and <u>the same flavour</u> neutrino.



$\alpha = e, \mu, \tau$ $\quad |\nu_\alpha\rangle$

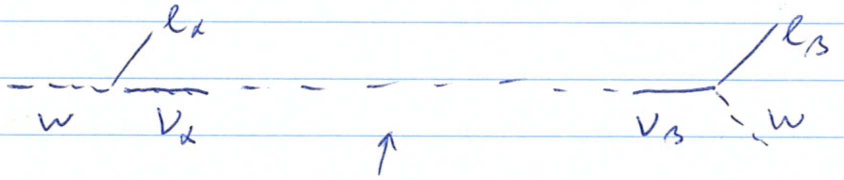
On the other hand, the mass eigenstates $|\nu_i\rangle$ $i = 1, 2, 3$ have a definite mass m_i.

Writing the connection between the two types of states

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle \quad \text{or} \quad |\nu_i\rangle = \sum_\alpha U_{\alpha i} |\nu_\alpha\rangle$$

U: Pontecorvo-Maki-Nakagawa-Sakata matrix.

Suppose we have a source of neutrino's of flavour α. Elsewhere we have a detector capable of measuring neutrino's of flavour β (by detecting corresponding lepton l_β)



propagation of mass eigenstates

$$\mathrm{Amp}(\nu_\alpha \to \nu_\beta) = \sum_i U^*_{\alpha i} \, \mathrm{Prop}(\nu_i) \, U_{\beta i}$$

Prop (ν_i) : plane wave solution of Schrödinger eq:

$$|\nu_i(t)\rangle = |\nu_i(0)\rangle e^{-iE_it}$$

To start easy, let's assume 2 flavours only : ν_α, ν_β , ν_1, ν_2

$$U^* = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \qquad \Big(\text{and } U = \begin{pmatrix} \cos\theta & -\sin \\ \sin\theta & \cos \end{pmatrix}$$

then the probability to detect flavour β when starting out with flavour α is :

$$P(\nu_\alpha \to \nu_\beta) = |Amp(\nu_\alpha \to \nu_\beta)|^2 = \Big|\sum_i U^*_{\alpha i}\, e^{-iE_it}\, U_{\beta i}\Big|^2$$

$$= \sin^2 2\theta \left[1 - \cos^2\left(\tfrac{1}{2}(E_1 - E_2)\right)t\right]$$

$$E_1 - E_2 = \sqrt{p^2 + m_1^2} - \sqrt{p^2 + m_2^2} \approx \frac{m_1^2 - m_2^2}{2p} \approx \frac{m_1^2 - m_2^2}{2E} = \frac{\Delta m^2_{12}}{2E}$$

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \, \sin^2\left(\frac{\Delta m^2}{4E} \cdot t\right)$$

$$= \sin^2 2\theta \, \sin^2\left[1.27 \, \Delta m^2 (eV^2) \cdot \frac{L(km)}{E(GeV)}\right]$$

The above equations assume propagation in vacuum.

<u>Some observations</u> :

- $\beta \neq \alpha$ only if $\Delta m^2 \neq 0$
  Observation of neutrino oscillations $\Rightarrow$ neutrino's have mass
- We can only say something about Δm^2, not about m
- $\beta \neq \alpha$ only if U non-diagonal $(\theta \neq 0)$
  $\Rightarrow$ mixing

- $\sin^2(t)$, or $\sin^2\left(\frac{L}{E}\right)$ implies: oscillation back-and-forth

- ν oscillations do not change the total flux, only the distribution over different flavours

- Experimental approach:
  - disappearance measurements $\left(P(\nu_\alpha \to \nu_\alpha) \neq 1\right)$
  - appearance measurements $\left(P(\nu_\alpha \to \nu_\beta) \neq 0\right)$

A specific choice of L/E is sensitive to a specific Δm^2
→ play with beam, detector distance.

Experimental evidence:

▷ Solar neutrino deficit

- Davis, Homestake mine $\nu_e + {}^{37}Cl \to {}^{37}Ar + e^-$ $E_\nu > 0.8$

  prediction: $9.3^{+1.2}_{-1.4}$ SNU

  measurement: 2.33 ± 0.25 SNU

  $1\ \text{SNU} = \dfrac{1\ \nu\ \text{interaction}}{10^{36}\ \text{Cl atoms} \cdot s}$

- Superkamiokande low E, but directional

  $\dfrac{N_{obs}}{N_{th}} = 0.47 \pm 0.02$ $E_\nu > 5$ MeV

- Gallium experiments $\nu_e + {}^{71}Ga \to {}^{71}Ge + e^-$

  sensitive to low energy ν_e (0.25 MeV)

  prediction: 129^{+8}_{-6} SNU

  measurement: 66.1 ± 3.1 SNU

SNO: 1000 tons heavy water

CC interactions of ν_e : $\nu_e + D \to p + p + e$

electron scattering of ν_e : $\nu_e + e \to e + \nu_e$ (CC)

NC interactions of all ν : $\nu_x + D \to p + n + \nu_x$

ES ~~of~~ of all ν : $\nu_x + e \to \nu_x + e$ (NC)

Result : sum of flux agrees well with predictions.
ν_e flux only 1/3 of total

▷ Atmosferic neutrino's:

- Deficit seen in ν_μ component compared to ν_e component

Naive expectation:

$$p + A \to \pi\,(K) + X$$

$$\pi \to \mu + \nu_\mu \qquad \mu \to e + \nu_e + \nu_\mu$$

Kamiokande : $R = \dfrac{(\nu_\mu/\nu_e)_{data}}{(\nu_\mu/\nu_e)_{MC}} \simeq 0.7 \pm 0.1$

SuperK: clear dependence on zenith angle = L

- Accelerator expts: K2K $\langle E_\nu \rangle = 1.3$ GeV L: 250 km
  MINOS multi-GeV wide-band beam L: 7
  iron-scintillator
  OPERA 17 GeV, L = 730 km
  Looks for ν_τ appearance
  emulsion

Consistent interpretation: (atmosferic ν only + accelerator)

$$\sin^2 2\Theta \sim 1 \quad (> 0.95)$$

$$\Delta m^2 = 2.32 \cdot 10^{-3}\ eV^2$$