Fundamental Forces

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TRIUMF

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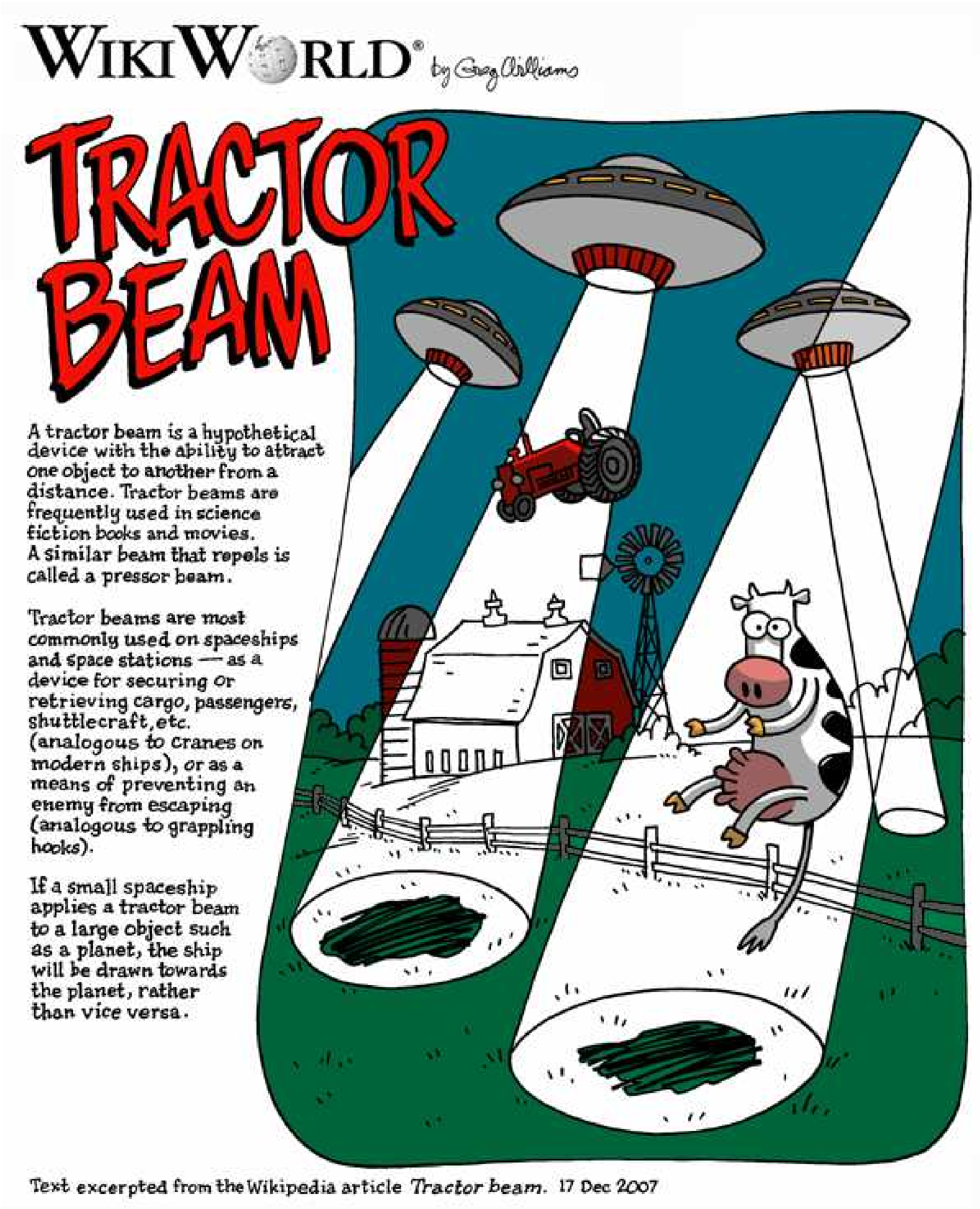
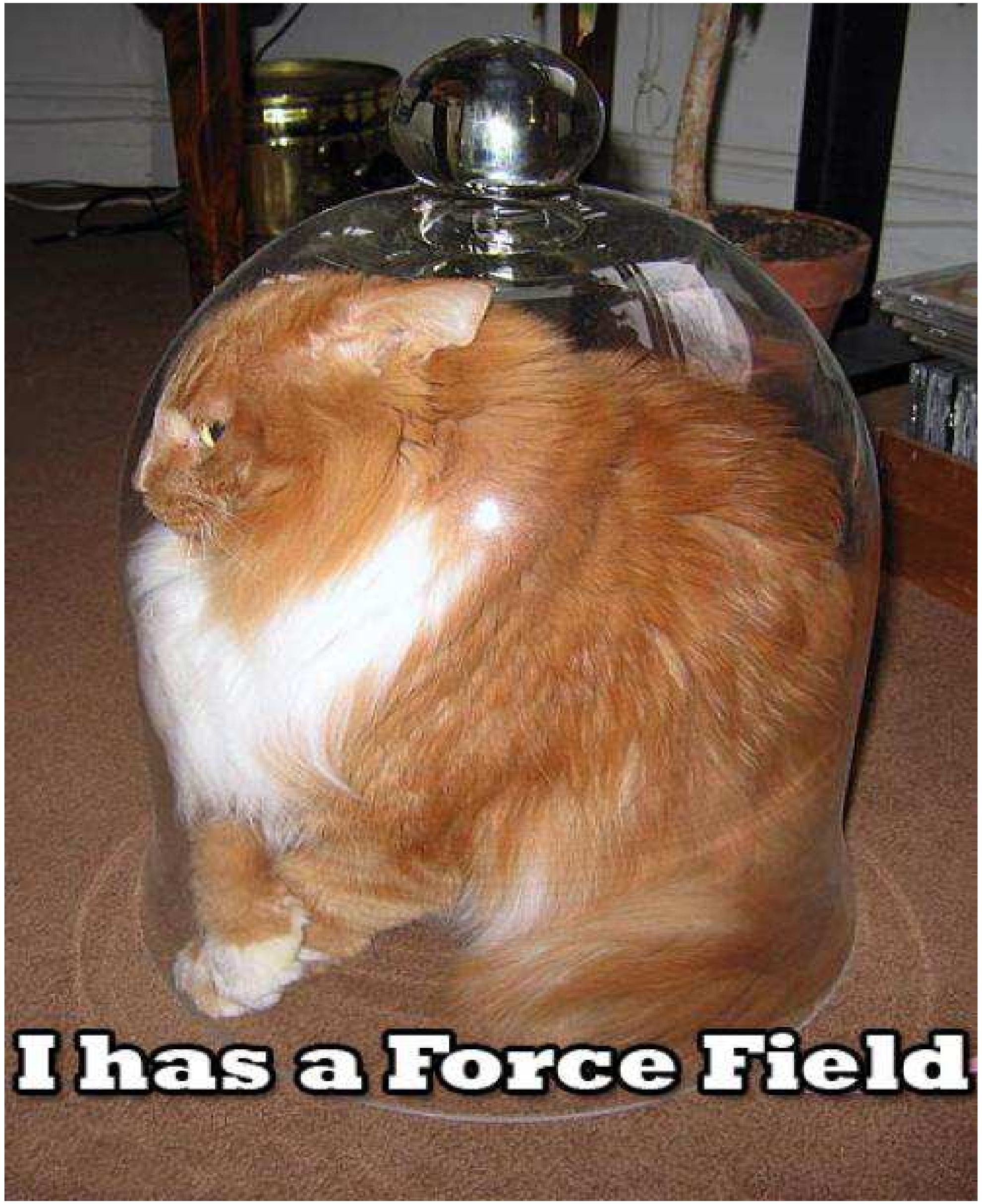
Aside: TRIUMF Run/Walk Group

- http://www.triumf.ca/triumf-social-club/triumf-walk-run-group/
- Group runs/walks on Tuesdays and Thursdays at 12pm.

  All abilities welcome!
- Benefits:
  - improve your fitness!
  - meet new people!
  - commune with nature!
  - get rained on!

- 

- Not a fundamental force . . .



- Also not a fundamental force . . .

What Do We Mean By Fundamental?

- Example: Electromagnetism (EM)
  - electric forces
  - magnetic forces
  - Van der Waals forces
  - radio waves
  - rainbows
  - . . .

- These different phenomena are all manifestations of EM.

  $\Rightarrow$ EM is said to be a fundamental force.

Fundamental and Elementary

- Fundamental forces are the ways in which elementary particles interact with each other.
- "Elementary" = can't be split into smaller things.
- The Standard Model:

Fermions

u	c	t
d	s	b
ν_e	ν_μ	ν_τ
e	μ	τ

Bosons

γ
g
W^{+-}
Z^0
h

• In stuffed toy form:

The Four Fundamental Forces *

1. Electromagnetism (EM) – binds atoms, light, shocks
2. Strong – holds nuclei together
3. Weak – source of nuclear decays
4. Gravity – why you're sitting here

* "Force" = way for particles to interact

Four "Fundamental" Forces *

1. Electromagnetism (EM) – binds atoms, light, shocks
2. Strong – holds nuclei together
3. Weak – source of nuclear decays
4. Gravity – why you're sitting here

- The Cold Hard Truth:
  - These forces might not actually be fundamental.
  - There may be more (or less) than four.

* "Force" = way for particles to interact

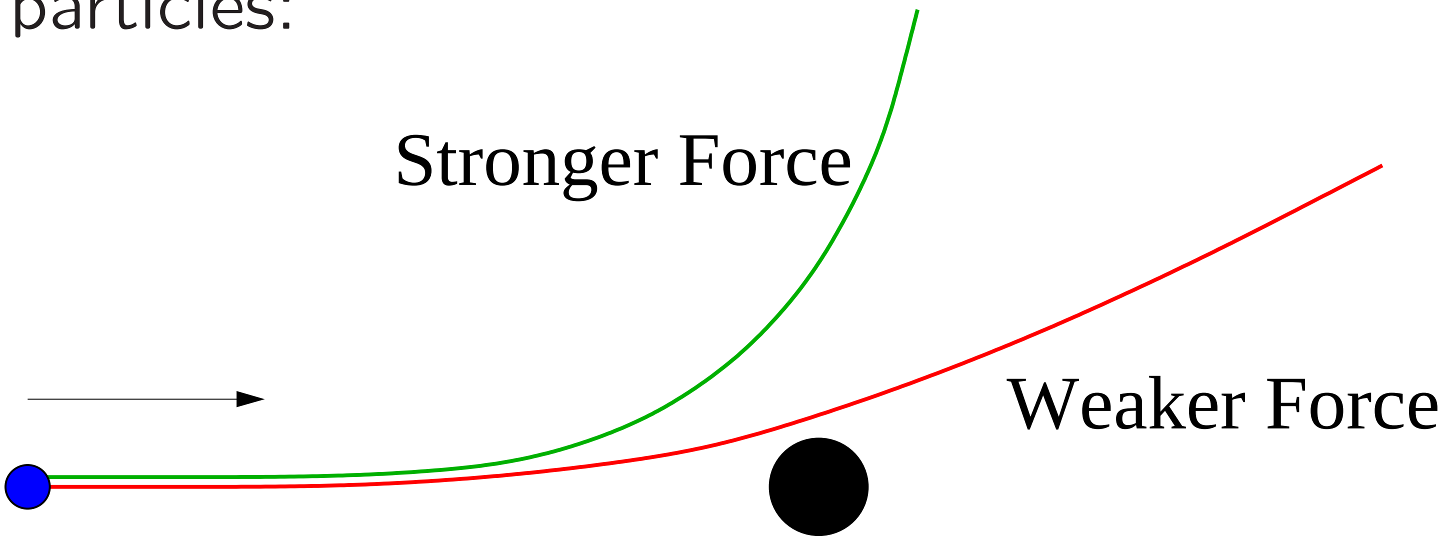
How Do We Measure Forces?

1. Pull two particles apart:

   → how much energy $V(r)$ does this take?

   Need really good tweezers . . .

2. Scatter particles:



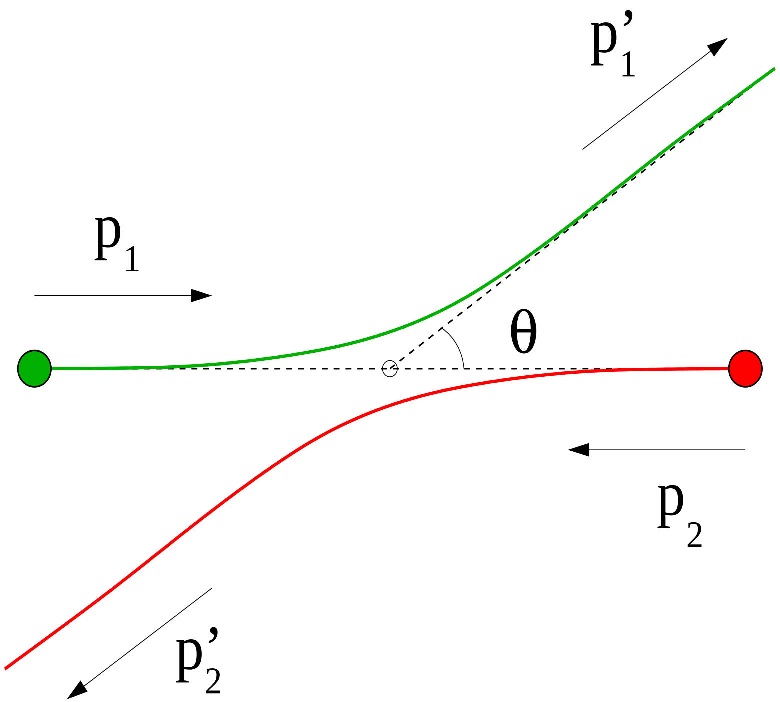
Stronger Force ↔ More Scattering

Forces and Scattering

$$\frac{d\sigma}{d(\cos\theta)}(p_1, p_2) = \text{differential scattering cross-section}$$
$$= \text{prob. for particles to scatter with angle } \theta$$
$$\propto |\mathcal{A}|^2$$

$\mathcal{A}$ is the quantum mechanical amplitude.

p_1, p_2 are the initial momenta of the particles.



- For non-relativistic scattering,

$$\mathcal{A} \propto \int d^3x \, e^{i\vec{q}\cdot\vec{x}} V(\vec{x}) \equiv \tilde{V}(\vec{q})$$

where $\vec{q} = (\vec{p} - \vec{p}')$ is the *momentum transfer*.

$\tilde{V}(\vec{q})$ is the *Fourier Transform* of the potential.

Also:

$$V(\vec{x}) = \int \frac{d^3q}{(2\pi)^3} e^{-i\vec{q}\cdot\vec{x}} \tilde{V}(\vec{q}).$$

- Scattering experiments teach us about forces!

Electromagnetism

- (Relativistic) Scattering experiments yield

$$\mathcal{A} \propto \tilde{V}(p) = \frac{Q_1 Q_2 e^2}{p^2},$$

where $p = (E, \vec{p})$ is the transferred 4-momentum,
$(Q_1 e)$ and $(Q_2 e)$ are the electric charges of the particles.

- Fourier transforming (in the non-relativistic limit) gives

$$V(\vec{x}) = -\frac{Q_1 Q_2 e^2}{4\pi} \frac{1}{r}.$$

- Science works!

Aside: Relativistic Particles and Quantum Mech.

- Describe particles by their 4-momentum:

$$p = (E, \vec{p}) \;, \quad \text{with} \quad p^2 \equiv E^2 - \vec{p}^2 \qquad (c = 1)$$

- An observed particle of mass m has $p^2 = m^2$.

$$\Rightarrow \;\; E = \sqrt{m^2 + \vec{p}^2}$$

- An unobserved particle can have other values of p^2.

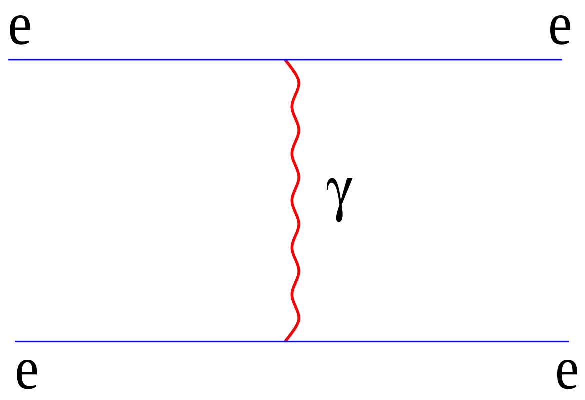
  The relative quantum mechanical amplitude is:

$$\mathcal{A}(p^2) \;=\; \frac{1}{p^2 - m^2}$$

- Amplitude for electromagnetic scattering:

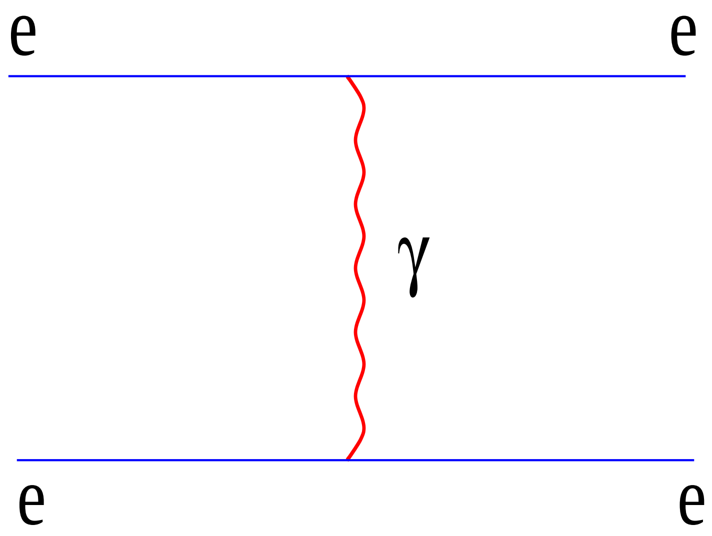
$$\mathcal{A} \propto \tilde{V}(p) = \frac{Q_1 Q_2 e^2}{p^2}$$

- Interpret the electromagnetic force as being *mediated* by a massless particle - the photon.

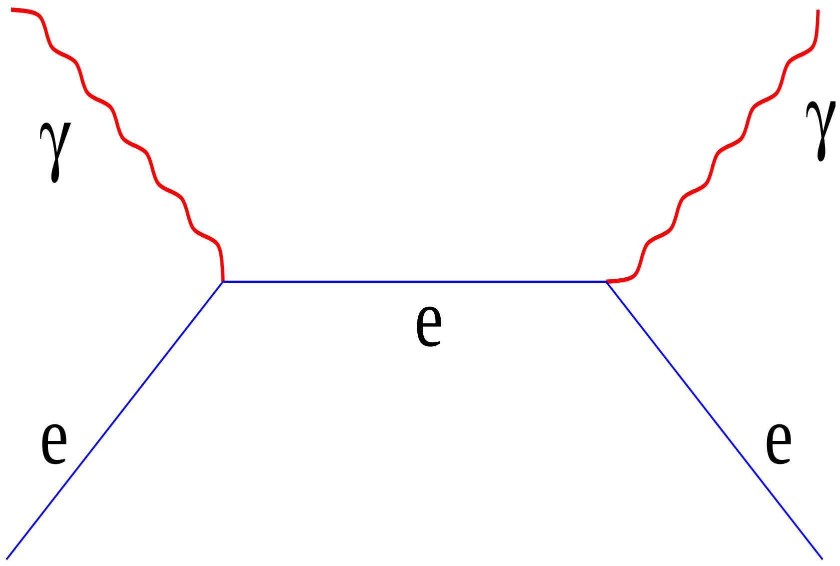


- The photon travels at the speed of light.
  In fact, the photon is a particle of light (or EM radiation).

- Feynman Diagram – electron scattering:



- Feynman Diagram – Compton scattering:



- Electromagnetism has a $U(1)_{em}$ *gauge symmetry*.

  The Hamiltonian for EM is invariant under:

$$
\begin{aligned}
\psi(x) &\to e^{iQ\alpha}\psi(x) && \text{(charged particle wavefnctn)}\\
\phi(x) &\to \phi(x) - \frac{1}{e}\frac{\partial\alpha}{\partial t} && \text{(scalar EM potential)}\\
\vec{A}(x) &\to \vec{A}(x) - \frac{1}{e}\vec{\nabla}\alpha && \text{(vector EM potential)}
\end{aligned}
$$

  for any function $\alpha(x)$.

- This symmetry COMPLETELY fixes how the photon couples to charged matter.

  $\Rightarrow$ all of electromagnetism follows from this simple gauge symmetry principle!

Aside: General Structure of $\tilde{V}(p)$

- We'll see that $\tilde{V}(p)$ has the same general structure for all forces we will look at:

$$\tilde{V}(p) \; = \; g^2 \times S \times \left(\frac{1}{p^2 - m^2} \right)$$

Here,

$$\begin{aligned} g &= \text{dimensionless coupling strength of the force} \\ S &= \text{dependence on particle spins} \\ \left(\frac{1}{p^2 - m^2} \right) &= \text{propagation of the force mediator} \end{aligned}$$

- I won't say much at all about S today.

The Strong Force

- Binds quarks into baryons and mesons, holds nuclei together.
- baryon $=$ qqq bound state
  e.g. $p = (uud)$, $n = (udd)$
- meson $=$ $q\bar{q}'$ bound state
  e.g. $\pi^0 = (u\bar{u}, d\bar{d})$, $K^+ = (u\bar{s})$
- ${}^{A}_{Z}X$ nucleus $=$ [Z p + (A-Z) n] bound state
  e.g. ${}^{4}_{2}He = 2\,p + 2\,n$, ${}^{16}_{8}O = 8\,p + 8\,n$
- Of the elementary particles we have discovered, only quarks and gluons feel the strong force.

- Scattering experiments tell us that:

$$\tilde{V}(p) = \begin{cases} \frac{g_s^2(p^2)}{p^2}, & p^2 \gtrsim \text{GeV}^2, \quad \text{quark scattering} \\ \\ \frac{g_{NN\pi}^2}{p^2 - m_\pi^2}, & p^2 \lesssim \text{GeV}^2, \quad \text{nucleon scattering} \end{cases}$$

- Why do we think both come from the same basic force?

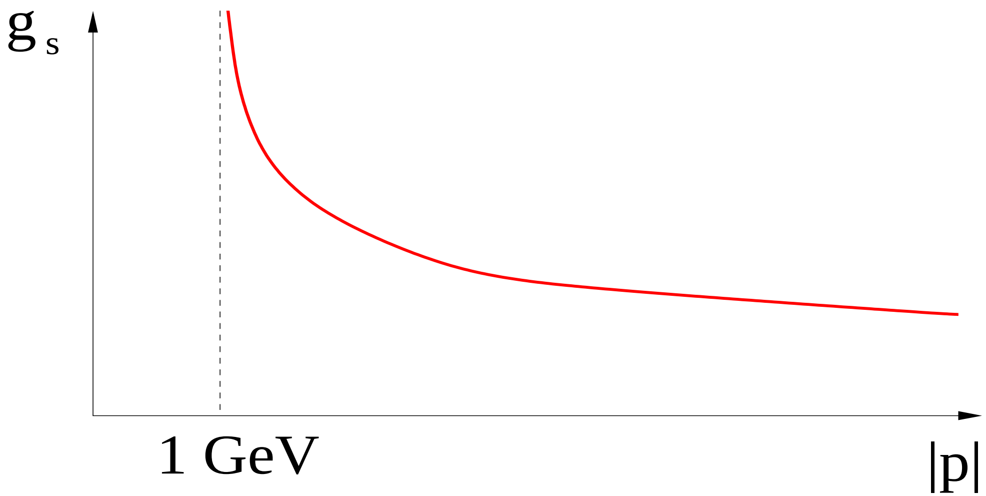
- Why don't we see quarks at low energies?

- Start with quark scattering ($p \gtrsim$ GeV):

$$\tilde{V}(p) \propto \frac{g_s^2}{p^2}$$

- $1/p^2 \Rightarrow$ massless mediator – the gluon.
- g_s describes the strength of the force.

  It depends on $|p|$:



- At $|p| \sim 1$ GeV the coupling blows up!

  This confines quarks and gluons into baryons and mesons:

$$V(\vec{x}) \sim -\frac{1}{r} + \Lambda^2 r, \qquad \Lambda \sim \text{GeV} \sim fm^{-1}.$$

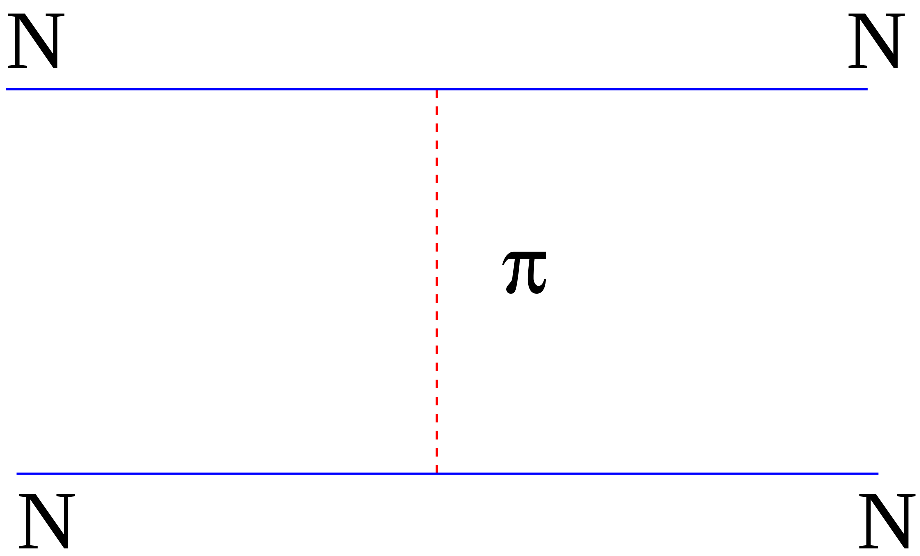
- At lower energies, look at nucleon scattering ($p \ll$ GeV)

$$\tilde{V}(p) = \frac{g_{NN\pi}^2}{p^2 - m_\pi^2}$$

The force is mediated (mostly) by pions.

$g_{NN\pi}$ is the residue of the strong force after confinement.

(Like van der Waals forces between neutral atoms.)



- Fourier transforming $\tilde{V}(p)$ gives

$$V(\vec{x}) = -\frac{g^2_{N\pi\pi}}{4\pi}\frac{1}{r}\,e^{-m_\pi r}$$

"Yukawa" force with range $r \sim 1/m_\pi \sim 1\,fm$.

- This is the typical separation between nucleons in nuclei!

  (Yukawa proposed the pion based on the range of the force.)

- The strong force is based on a $SU(3)_c$ gauge symmetry.

- $U(1) = 1 \times 1$ unitary matrices = phase transformations.

- $SU(N) = N \times N$ unitary matrices with (determinant = 1).

- $SU(3)_c$ interchanges the 3 "colour" charges carried by quarks.

  → strong force = "quantum chromodynamics" = QCD

- This symmetry COMPLETELY fixes the strong force!

- Gluons also carry colour charge.

  (Photons have no EM charge.)

The Weak Force

- Allows decays forbidden by the EM and strong forces:

$$\begin{aligned} n &\to p\,\bar{\nu}_e\,e^- \quad (d \to u\bar{\nu}_e e^- \text{ at the quark level}) \\ \pi^- &\to \bar{\nu}_\mu\,\mu^- \quad (d\bar{u} \to \bar{\nu}_\mu \mu^- \text{ at the quark level}) \\ b &\to c\,\bar{\nu}_e\,e^- \\ \mu^- &\to \nu_\mu\,\bar{\nu}_e\,e^- \end{aligned}$$

  These decays are very slow compared to EM or strong, but they are the only ones that mix "flavours".

- The weak force is much more interesting above 100 GeV.

- At lower energies, $|p| \ll 100\,\text{GeV}$, scattering gives

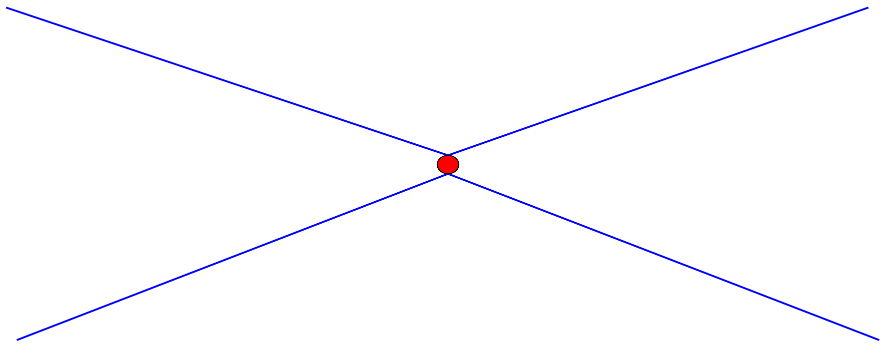
$$\tilde{V}(p) \simeq constant \sim -G_F \equiv -\frac{g_w^2}{m_W^2}$$

with $g_w \simeq 0.6$, $m_W \simeq 80\,\text{GeV}$.

- Fourier transforming gives

$$V(\vec{x}) \simeq -G_F\,\delta^{(3)}(\vec{x})$$

$\Rightarrow$ zero range "point interaction"



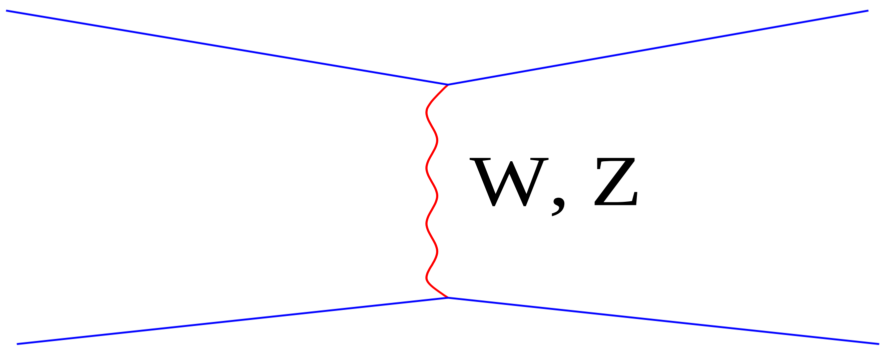
- The party starts at higher energies, $|p| \sim 100\,\text{GeV}$:

$$\tilde{V}(p) \sim \frac{g_w^2}{p^2 - m_W^2}, \quad \frac{g_w^2}{p^2 - m_Z^2}$$

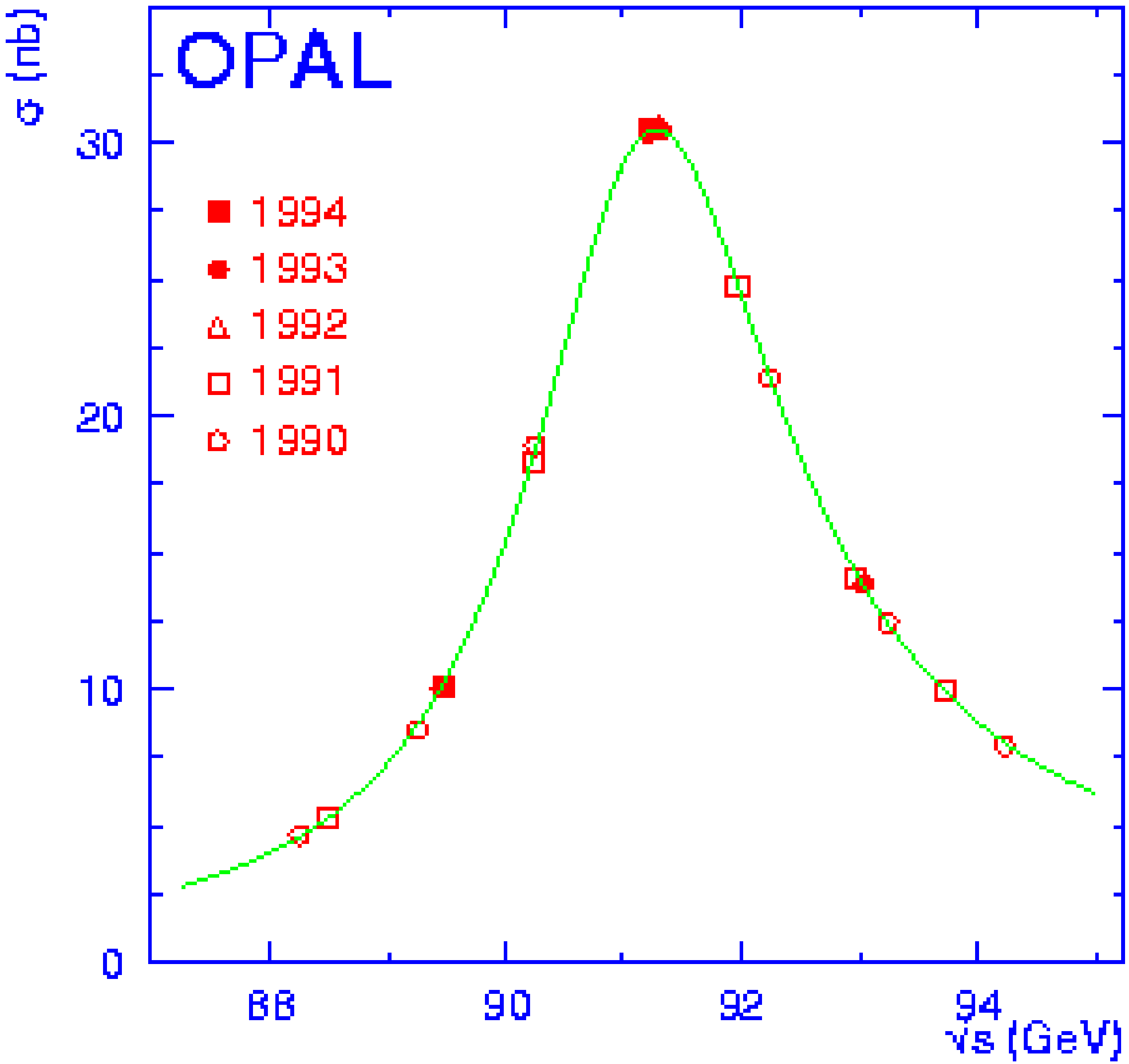
with $g_w \simeq 0.65$, $m_W \simeq 80.4\,\text{GeV}$, $m_Z \simeq 91.2\,\text{GeV}$.

- For $|p| \ll m_W$ this reduces to what we had before.

- Looks like a force mediated by particles with masses m_W, m_Z.



- $W^{\pm}$ and Z^0 spin–1 bosons were discovered in the 1980's.



OPAL
σ (nb)
30
20
10
0
1994
1993
1992
1991
1990
88
90
92
94
√s (GeV)

Electroweak Unification

- A gauge symmetry principle joins the weak and EM forces into a single *electroweak force*.
- The symmetry group is $SU(2)_L \times U(1)_Y$, contains $U(1)_{em}$.
- Most of this symmetry is "hidden" at low energies. Only the $U(1)_{em}$ subgroup of EM remains unhidden.
- Hiding the symmetry means:
  - $W^{\pm}$ and Z^0 gauge bosons acquire masses
  - the weak force has a finite range $\sim m_W^{-1}$
  - the weak force is much weaker than EM for $|p| \ll m_W$

- $SU(2)_L \times U(1)_Y$ has coupling constants g and g'.

  They are related to g_w and e by

$$g_w = g, \qquad e = gg'/\sqrt{g^2 + g'^2}.$$

- A spin–0 Higgs boson particle is thought to induce this electroweak symmetry breaking.

- We have just found a new particle with the right properties!

More Forces?

- The Higgs is also thought to generate fermion masses.

- If it does, there are also new "Higgs forces".

  For scattering of two fermions with masses m_1 and m_2,

$$\tilde{V}(p) = \frac{(m_1 m_2/v^2)}{p^2 - m_h^2}$$

with $m_h \simeq 125\,\text{GeV}$ and $v = 174\,\text{GeV}$.

- This is a new Yukawa-type force:

$$V(\vec{x}) = -\frac{(m_1 m_2/v^2)}{4\pi}\frac{1}{r}e^{-m_h r}.$$

- The coupling strength to a fermion of mass m is m/v.

Fewer Forces?

- Strong and Electroweak Couplings: $g_s > g > g'$.

  This is at $|p| \sim 100\,\text{GeV}$.

  ($g_s \sim 1$, $g \sim 0.65$, $g' \sim 0.35$)

- All three couplings depend on the scattering energy:

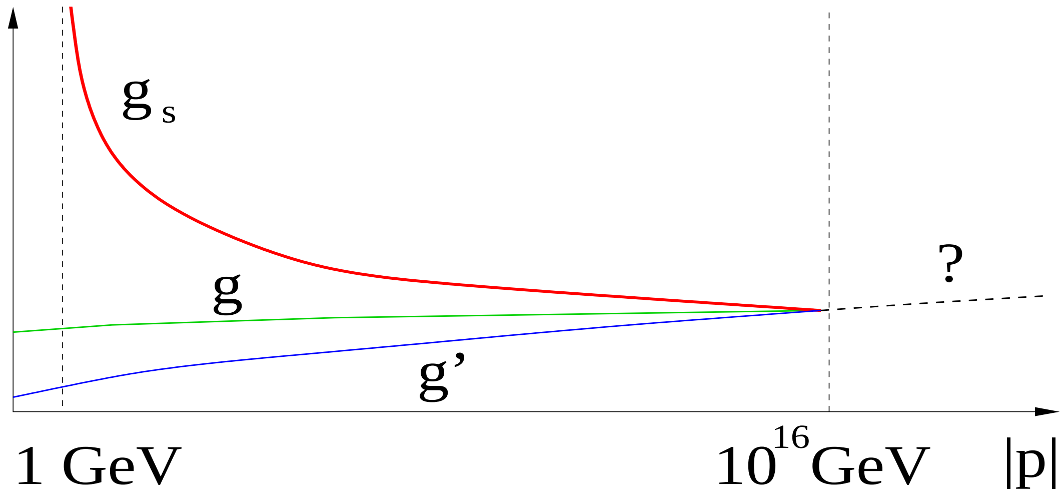
  g_s decreases going to higher energies

  g, g' increase going to higher energies

- Does the strong force get weaker than the weak force?

- Maybe – depends on what new physics is around.

- With no new physics (except maybe a little supersymmetry):



- It looks like the couplings all meet at a point!

  Maybe the strong and EW forces have a common origin?

- $SU(3)_c \times SU(2)_L \times U(1)_Y \quad \subset \quad SU(5),\ SO(10),\ E_6, \ldots$

  $\rightarrow$ gauge unification into a single force with coupling g_U?

- Symmetry breaking would split them into components.

Gravity

- Much weaker than the other three “fundamental” forces.

  $\Rightarrow$ almost always negligible in laboratory experiments

- Scattering of masses m_1 and m_2 gives ($p \ll M_{\mathrm{Pl}}$)

$$\tilde{V}(p) \sim \frac{m_1 m_2}{M_{\mathrm{Pl}}^2} \frac{1}{p^2},$$

  with $M_{\mathrm{Pl}} \simeq 2.4 \times 10^{18}\,\mathrm{GeV} = 1/\sqrt{8\pi G_N}$.

- This gives

$$V(\vec{x}) = -\frac{G_N m_1 m_2}{r}$$

- Yay!

- Interpret gravity as being mediated by a graviton.

  $\rightarrow$ massless spin–2 particle

- The graviton coupling strength to matter is m/M_{Pl}.

- Graviton couplings are fixed by a gauge symmetry.

  Symmetry Group = Local Coordinate Transformations

  $$x \rightarrow x'(x)$$

- This reproduces General Relativity at the classical level.

- We don't know what gravity does at energies above M_{Pl}, where quantum corrections become important.

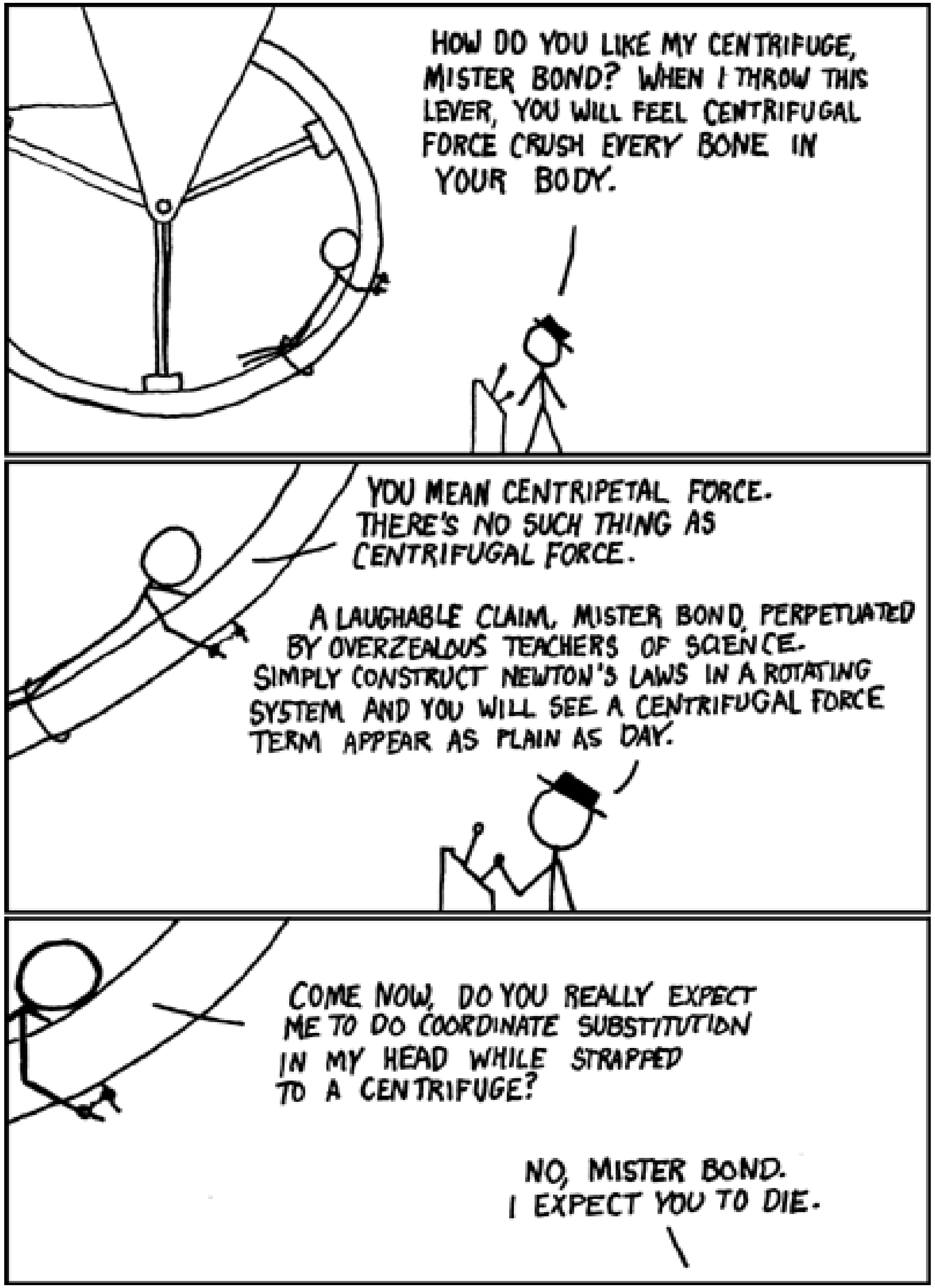
Summary – Fundamental Forces

- The 4FF are all based on gauge symmetries.

- But we think there are more forces out there.

- And the "fundamental" forces might not be fundamental.

- We hope to learn much more at the LHC!


HOW DO YOU LIKE MY CENTRIFUGE, MISTER BOND? WHEN I THROW THIS LEVER, YOU WILL FEEL CENTRIFUGAL FORCE CRUSH EVERY BONE IN YOUR BODY.
YOU MEAN CENTRIPETAL FORCE. THERE'S NO SUCH THING AS CENTRIFUGAL FORCE.
A LAUGHABLE CLAIM, MISTER BOND, PERPETUATED BY OVERZEALOUS TEACHERS OF SCIENCE. SIMPLY CONSTRUCT NEWTON'S LAWS IN A ROTATING SYSTEM AND YOU WILL SEE A CENTRIFUGAL FORCE TERM APPEAR AS PLAIN AS DAY.
COME NOW, DO YOU REALLY EXPECT ME TO DO COORDINATE SUBSTITUTION IN MY HEAD WHILE STRAPPED TO A CENTRIFUGE?
NO, MISTER BOND. I EXPECT YOU TO DIE.