PHYS 6610: Graduate Nuclear and Particle Physics I

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I. Tools

1. Introduction

Or: What NOVA Covered

See pdf: Handout Conventions, Essentials, Scattering

References: [HM1; HG 1; cursorily HG 5; PRSZ 1]

(a) Biased Remarks on Nuclear and Particle History

Many excellent accounts – see e.g. [Per, App. B]

1894 Henri Becquerel ruins a photographic plate by leaving uranium salt on top of it.

1898 Pierre and Marie Curie isolate the first radioactive elements and coin the term **radioactivity**.

1909 Ernest Rutherford, Hans Geiger and Ernest Marsden: Atoms mostly empty, with small, heavy core.

1930 Wolfgang Pauli makes up the neutrino to save energy: “Dear Radioactive Ladies and Gentlemen”.

1932 James Chadwick discovers the neutron, Carl David Anderson finds Dirac’s positron (first antiparticle, first (?) lost-and-found): Theorists move from just explaining to predicting.

1938 Otto Hahn and Fritz Strassmann split the nucleus but need their exiled collaborator Lise Meitner and her nephew Otto Fritsch to explain to them what they did. The latter do not get The Prize.

1945 Three nuclear fission bombs change the world.

1947 Powell et al. find Yukawa’s pion (nucleon-nucleon force particle).

1960’s Quip that the Nobel Prize should be awarded to the Physicist who does *not* discover a particle.

1961/2 Murray Gell-Mann, Yuvrai Ne’eman and others tame the particle zoo: flavours.

1964 Reading too much Joyce, Murray Gell-Mann and George Zweig hypothesize and baptise “quarks”.

1967/70 Stephen Weinberg, Abdus Salam and Sheldon Glashow unify electromagnetic and weak theory.

1973 Murray Gell-Mann, Harald Fritsch and Heiri Leutwyler formulate QCD.

1970’s Gerard ’t Hooft and many others: The Standard Model can be used to calculate & explain Nature.

1990 Stephen Weinberg suggests to describe Nuclear Physics as Effective Field Theory of QCD.

2012 CERN finds a boson right where Peter Higgs, Tom Kibble and François Englert left it.

Invitations to Stockholm: Physics above $1\,\mathrm{MeV}$

41 of 112 years saw prizes to Nuclear and Particle Physics – mostly Physics, few Chemistry.

1903 Radioactivity (C) Becquerel, P&M Curie
1908 Nucleus (C) Rutherford
1911 Ra, Po (C) M Curie
1927 Cloud chamber CRT Wilson
1935 Neutron Chadwick
1935 Transmutation (C) Joliot, Joliot-Curie
1936 Cosmic rays, positron Hess, CD Anderson
1938 Transmutation by neutrons Fermi
1939 Cyclotron Lawrence
1944 Fission (C) Hahn
Nuclear Magnetic Resonance Rabi
1948 More cloud chamber Blackett
1949 Pion as Nuclear Force (th) Yukawa
1950 Pion (discovery) Powell
1951 Transmutation by accelerators (C) Cockcroft, Walton
1952 Nuclear Magnetic Resonance Bloch, Purcell
1957 Parity violation (th) Lee, Yang
1958 Čerenkov radiation Čerenkov, Frank, Tamm
1959 Antiproton Segrè, Chamberlain

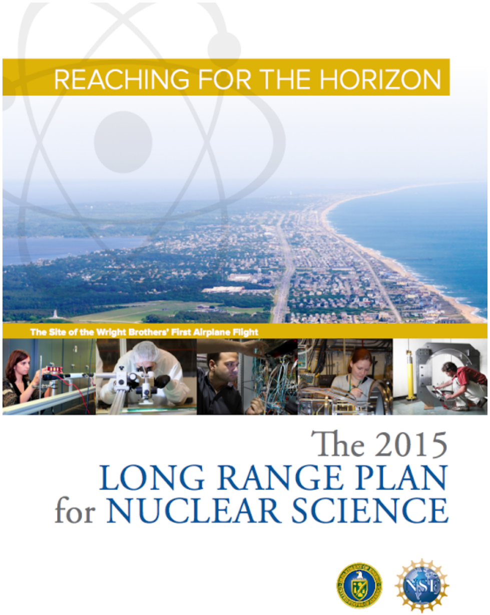
1960 Bubble chamber Glaser
1961 Proton form factor Hofstadter
1963 Nuclear shell structure Wigner, Goeppert-Mayer, Jensen
1965 QED Feynman, Schwinger, Tomonaga
1967 Stellar nucleosynthesis Bethe
1968 Nucleon resonances (exp) Alvarez
1969 Classify particle zoo (th) Gell-Mann
1975 Collective motion in nuclei A Bohr, Mottelson, Rainwater
1976 J/Ψ meson Richter, Ting
1979 Electroweak unification Glashow, Salam, Weinberg
1980 CP-violation (exp) Cronin, Fitch
1982 Renormalisation group KG Wilson
1983 Nucleosynthesis Chandrasekhar, Fowler
1984 W, Z bosons Rubbia, van der Meer
1988 Neutrino beam, ν_μ Lederman, Schwartz, Steinberger
1990 Deep inelastic scattering Friedman, Kendall, Taylor
1992 Multiwire proportional chamber Charpak

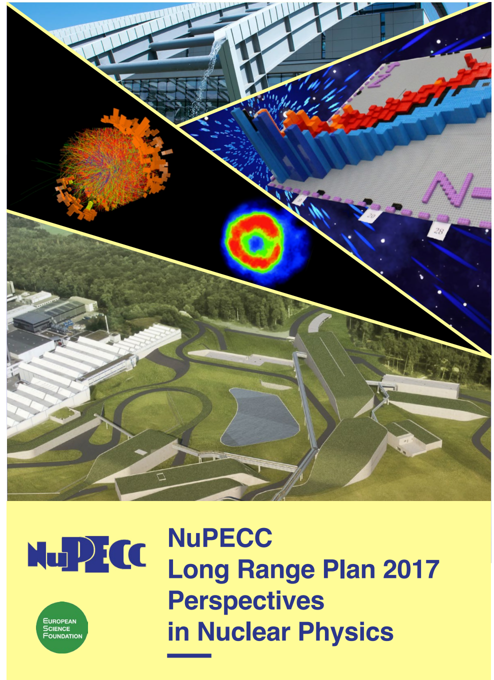
1995 Neutrino discovery, τ lepton Perl, Reines
1999 Renormalisability 't Hooft, Veltman
2002 Cosmic neutrinos Davis, Koshiba, Giacconi
2004 Asymptotic freedom Gross, Politzer, Wilczek
2008 Spontaneous symmetry breaking, CKM Kobayashi, Maskawa, Nambu
2013 Higgs mechanism (th) Englert, Higgs
2015 Neutrino oscillation Kajita, McDonald

Future (safe bets):
Higgs (exp), DIS (th), lattice-QCD, EFT, ?

Nuclear/Particle Priorities Encoded in Long-Range Plans

The steering tools on which the US Department of Energy (DOE), the US National Science Foundation (NSF) and their European counterparts base their funding priorities.





US NSAC:
Nuclear Science Advisory Committee
Long Range Plan 2015 (link)

EU NuPECC:
Nuclear Physics European Collaboration Committee
Long Range Plan 2017 (link)

Handout: Conventions and Bare Essentials for HW and Beyond

You will find much of what we will do today here (link).

Nuclear Physics: Conventions

v1.0, Jan 2016

The Natural System of Units is particularly popular in Nuclear and High-Energy Physics since as many fundamental constants as possible have as simple a value as possible (see [MM]!).
Set the speed of light and Planck's quantum to $c = \hbar = 1$. This expresses velocities in units of c, and actions and angular momenta in units of $\hbar$. Then, only one fundamental unit remains, namely either an energy- or a length-scale. Time-scales have the same units as length-scales. We also set Boltzmann's constant $k_B = 1$, so energy and temperature have the same units. Now one only memorises a handful of numbers. [Setting Newton's gravitational constant $G_N = 1$ eliminates *any* dimension-ful unit – only String Theorists do that.]

Electrodynamic Units: The Rationalised Heaviside-Lorentz system will be used throughout. Formally, it can be obtained from the SI system by setting the dielectric constant and permeability of the vacuum to $\epsilon_0 = \frac{1}{\mu_0 c^2} = 1$. The system is uniquely determined by any two of the fundamental equations which contain $\vec{E}$ and a combination of $\vec{E}$ and $\vec{B}$. More on systems, units and dimensions e.g. in [MM].

Charges $Q = Ze$ are measured in units Z of the elementary charge $e > 0$; electron charge $-e < 0$.

Lagrangean: $\mathcal{L}_{\text{elmag}} = -\frac{1}{4} F^{\mu\nu} F_{\mu\nu} \implies$ Maxwell's equations: $\partial_\mu F^{\mu\nu} = j^\nu$

Lorentz force: $\vec{F}_L = Ze[\vec{E} + \vec{\beta} \times \vec{B}]$; Coulomb's law: $\Phi(r) = \frac{Ze}{4\pi\, r}$

"Restoring" SI units from "natural units": Multiply by $c^\alpha\, \hbar^\beta\, k_B^\gamma\, \epsilon_0^\delta$ and determine the exponents such that the proper SI unit remains, using $[c]$: $[\mathrm{m\,s^{-1}}]$, $[\hbar]$: $[\mathrm{kg\,m^2\,s^{-1}}]$, $[k_B]$: $[\mathrm{m^2\,kg\,s^{-2}\,K^{-1}}]$ and $[\epsilon_0]$: $[\mathrm{C\,V^{-1}\,m^{-1}} = \mathrm{C^2\,s^2\,m^{-2}\,kg^{-1}}]$. Example: $E = m \implies E = m\, c^\alpha\, \hbar^\beta\, k_B^\gamma\, \epsilon_0^\delta$, and you have to convert $\mathrm{kg\,m^2/s^2}$ into kg, i.e. add two powers of m/s, so that $\alpha = 2, \beta = \gamma = \delta = 0$.

Conventions Relativity: Einstein Σummation Convention; "East-coast" metric $(+---)$:

$$A^2 \equiv A^\mu\, A_\mu := (A^0)^2 - \vec{A}^2.\ \text{Velocity } \beta,\ \text{Lorentz factor } \gamma = \left(1-\beta^2\right)^{-1/2}.$$

Conventions QFT: "Bjørken/Drell": [HM, PS] – close to [HH], but fermion norms different:

Quantised complex scalar: $\Phi(x) = \int \frac{\mathrm{d}^3k}{(2\pi)^3} \frac{1}{\sqrt{2E_k}} \left[a(\vec{k})\, \mathrm{e}^{-\mathrm{i}k\cdot x} + b^\dagger(\vec{k})\, \mathrm{e}^{+\mathrm{i}k\cdot x}\right]$ with $E_k := k^0 = +\sqrt{\vec{k}^2 + m^2}$

Minimal substitution in QED: $D^\mu = \partial^\mu + \mathrm{i}Ze\, A^\mu$; in non-Abelian gauge theories (QCD,...): $D^\mu = \partial^\mu - \mathrm{i}g\, A^\mu$.

$\gamma^5 = \mathrm{i}\gamma^0\gamma^1\gamma^2\gamma^3 = \gamma_5$; $2mP_+ := \sum_{s=\pm} u_s(p)\bar{u}_s(p) = \not{p} + m$, $-2mP_- := \sum_{s=\pm} v_s(p)\bar{v}_s(p) = \not{p} - m \implies P_+ + P_- = 1$

Elastic cross section (our convention) in cm: $\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \frac{1}{64\pi^2 s} |\overline{\mathcal{M}}|^2$; lab, $m = 0$: $\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \frac{1}{64\pi^2 M^2} \left(\frac{E'}{E}\right)^2 |\overline{\mathcal{M}}|^2$

Decay of particle with mass M (cm, our convention): $\Gamma[A \to B(\vec{p}') + C] = \frac{|\vec{p}'|}{8\pi M^2} \int \mathrm{d}\Omega\, |\overline{\mathcal{M}}|^2$

More cross section formulae & conventions in "**Summary Electron Scattering Cross Sections**" below.

Nuclear Physics: Some Oft-Overlooked Bare Essentials

Know these by heart! Physicists spend a lot of time solving complicated problems, so we want to always start with an idea of the result. We have ideas when we are hiking, cycling, in the shower, etc., and usually not on our desk. We discuss them with colleagues on the blackboard, and we cannot waste their and our time with looking stuff up. Therefore, we need to be able to do calculations without computers, books or calculators, i.e. in our head or with a piece of scrap paper and a dull pencil.
Here a list of numbers most commonly used for estimates, back-of-the-envelope calculations, etc. of the *Nuclear Physics tool-chest. You need them for that purpose but they are often overlooked.* You should know the following by heart when woken up at night. The list is not exhaustive, not meant to be relevant and may not be useful. Your mileage may vary. It's better to know too much than not enough. You should check these values, how they come about, and their limitations. Trivialities are not included, like most "Essentials' from Mathematical Methods [MM] (dimensional estimates, guesstimates, Natural System of Units). If you know more things worth remembering, let me know!
This is the list of *often-overlooked numbers, not of the minimum necessary* – **the minimum is much larger** (including names, spins, charges, masses of all fundamental particles, etc.).

Please turn over.

$\approx$: number rounded for easier memorising – it suffices to know the first significant figure.
$\widehat{=}$, $\widehat{\approx}$: correspondences are correct only in the natural system of units.

Quantity	**Value**
speed of light in vacuum	$c := 2.997\,924\,58 \times 10^8\ \mathrm{m\ s^{-1}}$(def.!)$\approx 3 \times 10^8\ \mathrm{m\ s^{-1}}$
energy electron gains when accelerated by 1 V	1 electron Volt (eV) $\approx 1.6 \times 10^{-19}$ Joule $= 1\frac{e}{[\mathrm{C}]}$ J
conversion factor	$1\ \mathrm{J} \approx 6 \times 10^{18}$ eV
typ. subatomic length-scale (proton/neutron size)	1 fermi (femtometre, fm) $= 10^{-15}$ m
conversion factor energy – length	$\hbar c \,\widehat{=}\, 1 = 197.327\ldots$ MeV fm ≈ 200 MeV fm
$\implies$ conversion factor distance – time (nat. units) (time for light to travel a typ. distance-scale)	$1\ \mathrm{fm} = 1\frac{\mathrm{fm}}{c} \,\widehat{\approx}\, \frac{1}{3} \times 10^{-23}$ s
conversion factor elmag.: fine-structure constant el. strength at atomic/nuclear/hadronic scales	$\alpha = \frac{e^2}{4\pi}\Big\vert_{\text{nat.+rat. HL}} = \frac{e^2}{4\pi\epsilon_0\hbar c}\Big\vert_{\text{SI}} \approx \frac{1}{137}$ (no units!)
conversion factor energy – temperature: $E = k_B T$	$1\ \mathrm{eV} \,\widehat{\approx}\, 11\,600$ Kelvin, $300\ \mathrm{K} \,\widehat{\approx}\, \frac{1}{40}$ eV
"classical" electron radius	$r_e = \frac{\alpha}{m_e c^2} = \frac{e^2}{4\pi\, m_e}\Big\vert_{\text{nat.+rat. HL}} \approx 3$ fm

Masses conversion factor: atomic unit $1\mathrm{u} = \frac{\text{mass } ^{12}\text{C atom}}{12} = \frac{1}{12} \times \frac{12\ \mathrm{g}}{6.022 \times 10^{23}} \approx \frac{1}{6} \times 10^{-23}$ g

electron	$m_e \approx 511$ keV	muon	$m_\mu \approx 110$ MeV $\approx 200\, m_e$	
nucleon	$M_N \approx 940$ MeV $\approx 1800\, m_e \approx 1$ GeV ≈ 1 u			
proton	$M_p \approx 938$ MeV	neutron	$M_n \approx 940$ MeV	$\implies$ p-n mass difference 1.3 MeV $\approx 3\, m_e$
pion	$m_\pi \approx 140$ MeV $\approx \frac{1}{7} M_N$	kaon	$m_K \approx 500$ MeV	ρ, ω mesons $m_\rho \approx m_\omega \approx 800$ MeV
Higgs boson	$M_H \approx 125$ GeV	W boson	$M_W \approx 80$ GeV	Z boson $M_Z \approx 90$ GeV

Scattering nuclear cross-section unit: 1 barn $b = 100\ \mathrm{fm}^2 = (10\ \mathrm{fm})^2 = 10^{-28}\ \mathrm{m}^2 \approx \frac{1}{400\ \mathrm{MeV}^2}$

"geometric" scattering: $\sigma_{\text{geometric}} = 4\pi\, a^2$.

Interpretation: (1) class. point particle on sphere, radius a, any energy; (2) QM zero-energy, scatt. length a.

Hierarchy of Scales	typ. energy	typ. momentum	typ. size/distance
nuclear structure	binding: 8MeV per nucleon	100 keV...1MeV	10fm ($\sim^{235}$U size)
few-nucleon	binding: deuteron: 2.2246MeV; ^{4}He: 24MeV	$m_\pi \approx 140$MeV	$\frac{1}{m_\pi} \approx 1.5$fm (Yukawa)
hadronic	$M_N, M_\rho \approx 1$GeV	1GeV (relativistic)	$\frac{1}{M_N} \approx 0.2$fm
particle	100GeV Z, W masses	100GeV (relativistic)	$\frac{1}{100\mathrm{GeV}} \approx 2 \times 10^{-3}$fm

Interaction Scales very rough – factors of 100 up or down are common

	strong (NN int.)	**strong** (qq int.)	**elmag**	**weak** (nuclear)	**weak** (hadronic)
range	$\frac{1}{m_\pi} \approx 1.4$ fm	$\frac{1}{1\ \mathrm{GeV}} \approx 0.2$ fm	∞	$\frac{1}{M_{W,Z}} \approx 0.01$ fm	
life time τ	10^{-22} s	10^{-23} s	10^{-20} s	10^{-10} s	10^{-9} s
decay width Γ	200 MeV		1 MeV	$\ll$ eV	
cross section σ	barn (NN@1MeV: 70b)	mb	μb	10^{-12} b $= 1$ pb	100 pb

Miscellaneous neutron lifetime: $\tau_n \approx 880$ s hadron size $R \approx 0.7$ fm hadronisation scale 1 GeV $\widehat{\widehat{=}}$ 0.2 fm

Weinberg mixing angle $\sin^2\theta_W \approx 0.22 \approx 1 - \frac{M_W^2}{M_Z^2}$ Fermi constant $G_F \approx \frac{\sqrt{2}\, g^2}{8M_W^2} \approx 1 \times 10^{-5}\ \mathrm{GeV}^{-2}$

running coupling constants: $\alpha(1\ \mathrm{MeV}) = \frac{1}{137}$; $\alpha(M_Z) = \frac{1}{128}$ $\alpha_s(2m_b \approx 10\ \mathrm{GeV}) \approx 0.2$; $\alpha_s(M_Z) \approx 0.118$

(b) Units & Conventions

– **Relativity:** Einstein Σum Convention; metric $(+---)$: $A^2 \equiv A^\mu A_\mu := (A^0)^2 - \vec{A}^2$

velocity β, Lorentz factor $\gamma = \left(1-\beta^2\right)^{-1/2}$

– **Natural System of Units**: $\boxed{\hbar = c = k_B = 1}$ $\Longrightarrow$ velocity in units of c. [MM 1]

Resolution at given momentum: Uncertainty Relation $\Delta p\, \Delta x \geq \hbar = 1$ $\Longrightarrow$ only *one* base unit

$$1 = \hbar\, c = 197.327\text{MeVfm} \qquad 11{,}605\text{K} = 1\text{eV}$$

Set base-unit to match Nuclear/Particle scales:

typ. length scale:	$1\text{fm} := 1 \text{ fermi} := 1 \text{ femtometre} = 1 \times 10^{-15}\text{m}$	$\approx$ N size
typ. time scale:	$\dfrac{1\text{fm}}{c} \approx \dfrac{1}{3} \times 10^{-23}\text{s}$	time for light to traverse N
typ. energy & momentum:	$1\text{GeV} = 1000\text{MeV} = 10^9 \text{ eV}$	$\approx$ N mass
typ. nuclear cross section:	$1 \text{ b} := 1\text{barn} := 1 \times 10^{-28}\text{m}^2 = (10\text{fm})^2 \approx \dfrac{1}{400\text{MeV}^2}$	

"geometric" scatter: class. point particle on hard sphere (any energy)/QM zero-energy scatt. length:

$\sigma_{\text{geom}} = 4\pi\, a^2 = 1 \text{ b} = (10\text{fm})^2 \Longrightarrow a \approx 3\text{fm}$ typ. heavy nucleus size (lead, Uranium) ✓

More Units

– **Electrodynamics:** Rationalised Heaviside-Lorentz units, electron charge $-e < 0$

$$\epsilon_0 = \frac{1}{\mu_0 c^2} := 1$$

$\Longrightarrow \mathcal{L}_{\text{elmag}} = -\frac{1}{4} F^{\mu\nu} F_{\mu\nu}$ — Maxwell: $\partial_\mu F^{\mu\nu} = j^\nu$ — Lorentz: $\vec{F}_L = Ze[\vec{E} + \vec{\beta} \times \vec{B}]$ — Coulomb: $\Phi(r) = \frac{Ze}{4\pi\, r}$

fine structure constant $\alpha := \frac{e^2}{4\pi\epsilon_0 \hbar c} = \frac{e^2}{4\pi} = \frac{1}{137} \Longrightarrow e \approx 0.30$ dimension-less

– **QFT conventions:** “Bjørken/Drell”: [HM] – close to Haberzettl (fermion norms different)

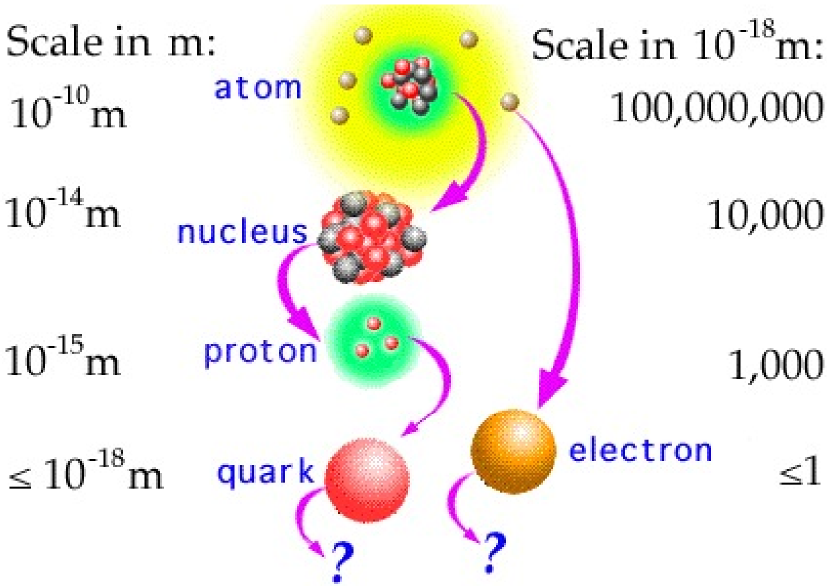
– **Restoring SI Units**: Throw in $\hbar^\alpha\, c^\beta\, k_B^\gamma\, \epsilon_0^\delta$ until SI units match: $E = m\, c^\alpha\, \hbar^\beta\, k_B^\gamma\, \epsilon_0^\delta \Longrightarrow \alpha = 2$.

– **Convenient mass conversion factor:**

$$1\text{u (atomic unit)} = \frac{\text{mass of } ^{12}\text{C atom}}{12} = \frac{1}{12} \times \frac{12\text{ g}}{6.022 \times 10^{23} (\text{Avogadro})} \approx \frac{1}{6} \times 10^{-23}\text{ g}$$

$$\Longrightarrow \text{nucleon mass} \approx 1\text{GeV} \approx \frac{1}{12}\, {}^{12}\text{C mass} \approx \frac{1}{6} \times 10^{-23}\text{ g}$$

Length Scales



"Atomic Physics"

"Nuclear Physics"

"Nuclear Structure"

"Nuclear Physics"

"Hadron Physics"

"Particle Physics"

Elementary? Strings? Preons?

(c) Hierarchy of Scales

	typ. energy	typ. momentum	typ. size
nuclear structure	binding: 8MeV per nucleon	$100\text{ keV}\ldots 1\text{MeV}$	10fm ($\sim {}^{235}\text{U}$ size)
few-nucleon	binding: 2.2MeV deuteron 24MeV ${}^{4}\text{He}$	$m_\pi \approx 140\text{MeV}$	$\frac{1}{m_\pi} \approx 1.5\text{fm}$ (Yukawa)
hadronic	$M_\text{N}, m_\rho \approx 1\text{GeV}$	1GeV (relativistic)	$\frac{1}{M_\text{N}} \approx 0.2\text{fm}$
particle	100GeV Z, W masses	100GeV (relativistic)	$\frac{1}{100\text{GeV}} \approx 2 \times 10^{-3}\text{fm}$

Difference "Low" – "High" Energy Physics Is Time-Dependent!

PHYSICAL REVIEW VOLUME 76, NUMBER 1 JULY 1, 1949

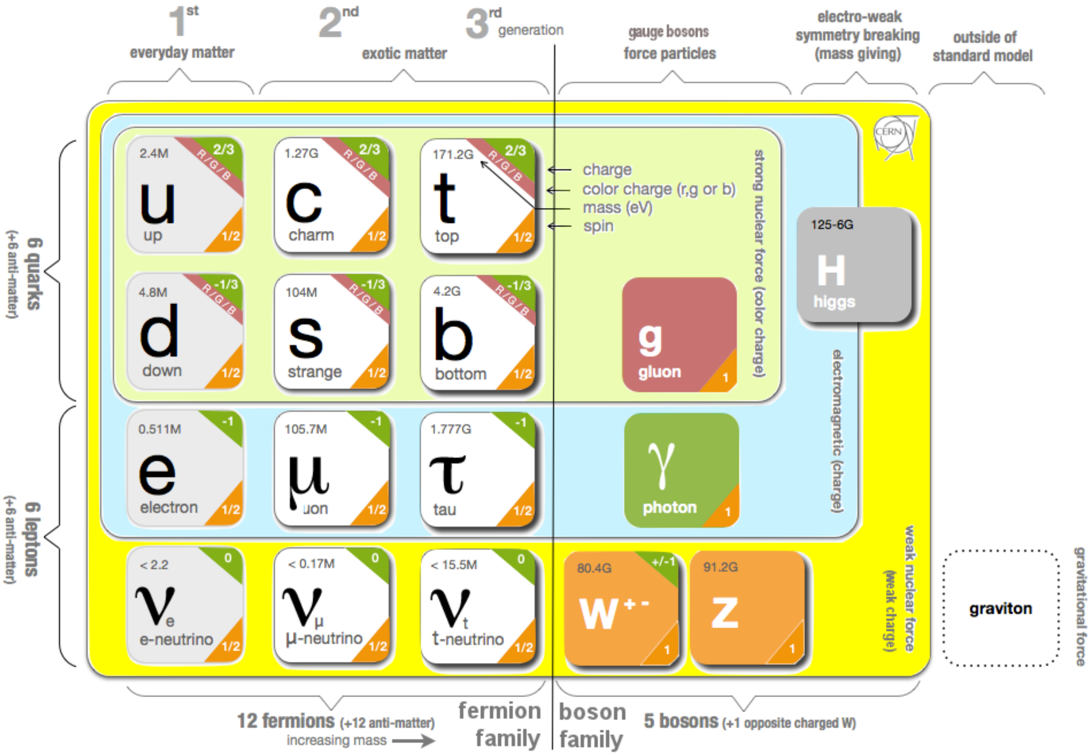
Bremsstrahlung in High Energy Nucleon-Nucleon Collisions

J. Ashkin and R. E. Marshak
University of Rochester, Rochester, New York

(Received March 22, 1949)

Formulas for the differential cross sections for the continuous γ-emission accompanying proton-neutron, proton-proton, neutron-neutron collisions have been derived. Numerical results are given for an incident nucleonic energy of 250 Mev.

(d) The Standard Model



Lepton / Quark Universality Hypothesis: Leptons / Quarks couple with same form & strengths.

Standard Model mass hierarchy not understood

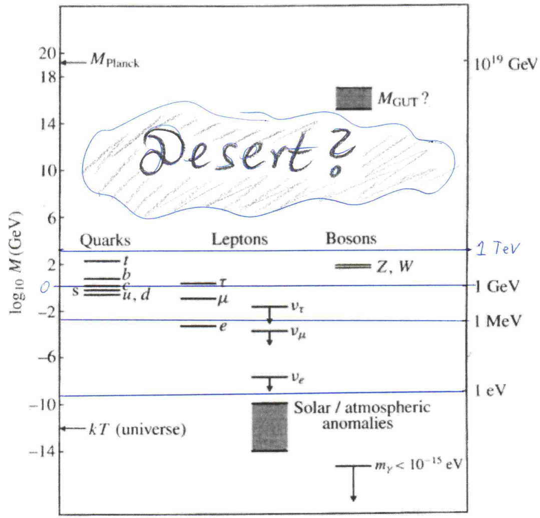
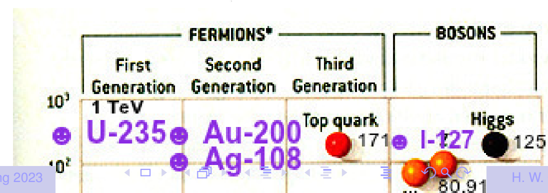


Fig. 1.7. The mass spectrum of leptons and quarks. The values shown for neutrinos are upper limits from direct measurements, and the solar and atmospheric neutrino anomalies (see Chapter 9) suggest even smaller masses. Other important mass scales are also shown: the Fermi or electroweak scale at 100 GeV, typified by the $W^\pm$ and Z^0 boson masses; the Planck mass scale, of order 10^{19} GeV, at which gravitational interactions are expected to become strong (see Chapter 2): and the value, $kT \simeq 1$ meV, of the cosmic microwave radiation ($T = 2.7$ K) in the universe today.



Some Important Particles, Their Masses and Contents

Fermions

electron ($J^P = \frac{1}{2}^+$) $m_e \approx 511\text{keV}$

muon ($\frac{1}{2}^+$) $m_\mu \approx 110\text{MeV} \approx 200\, m_\text{e}$

nucleon ($\frac{1}{2}^+$) $M_\text{N} \approx 940\text{MeV}$

$\approx 1800\, m_\text{e} \approx 1\text{GeV} \approx 1\text{ u}$

proton ($\frac{1}{2}^+$) $M_\text{p} \approx 938\text{MeV} \approx 6\pi^5 m_\text{e}$ (uud)

neutron ($\frac{1}{2}^+$) $M_\text{n} \approx 940\text{MeV}$ (udd)

$\Longrightarrow$ p-n mass difference $1.3\text{MeV} \approx 3m_\text{e}$

Bosons/Mesons

pion (0^-) $m_\pi \approx 140\text{MeV} \approx \frac{1}{7} M_\text{N}$ $\pi^+(u\bar{d})$, $\pi^-(\bar{u}d)$, $\pi^0(u\bar{u}, d\bar{d})$

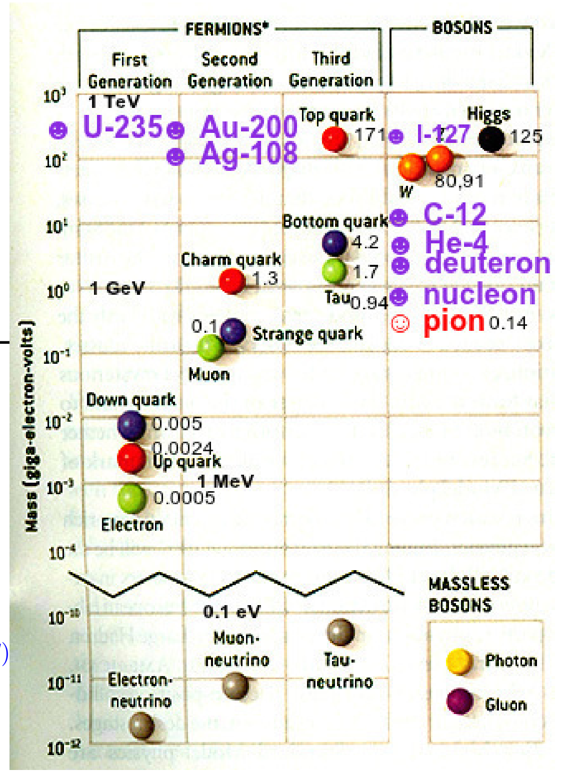
kaon (0^-) $m_\text{K} \approx 500\text{MeV}$ $K^+(u\bar{s})$, $K^-(\bar{u}s)$, $K^0(d\bar{s}, \bar{d}s)$

$\rho^{0,\pm}$, ω^0 (1^-) $m_\rho \approx m_\omega \approx 800\text{MeV}$ $(\bar{u}d, u\bar{d}, \bar{u}u, \bar{d}d)$

Higgs (0^+) $M_\text{H} \approx 125\text{GeV}$

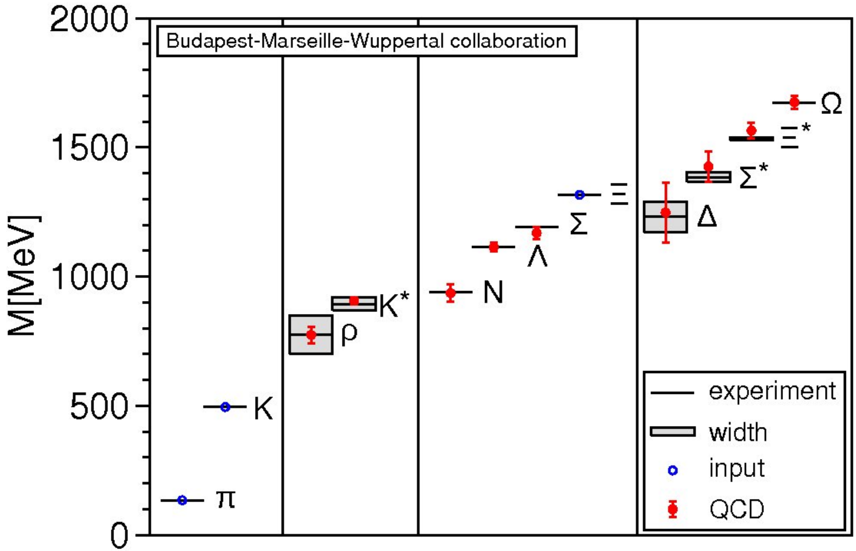
W boson (1^-) $M_\text{W} \approx 80\text{GeV}$

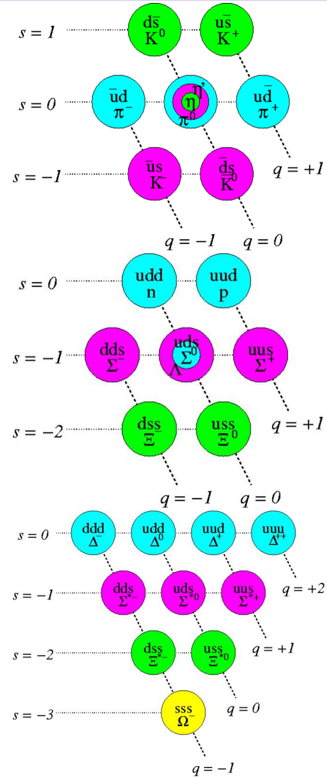
Z boson (1^-) $M_\text{Z} \approx 90\text{GeV}$



(e) Results of the Standard Model

Results of the Standard Model: Hadron Zoo





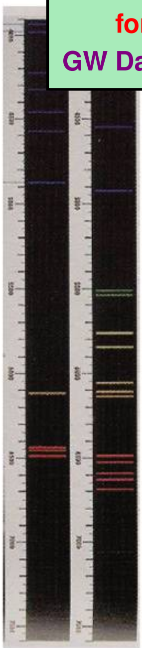
Valence Quarks determine charge,. . .

Mesons: Valence Quark-Antiquark **Baryons: 3 Valence Quarks**

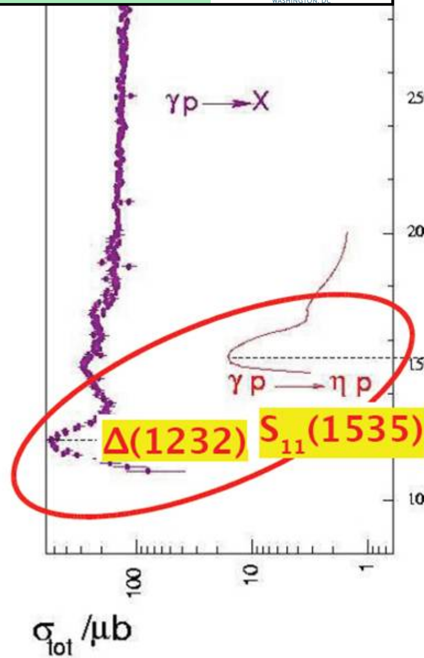
Results of the Standard Model: Baryon Resonances

QCD Partial Wave Analysis for Baryons (& Mesons):
GW Data Analysis Center DAC

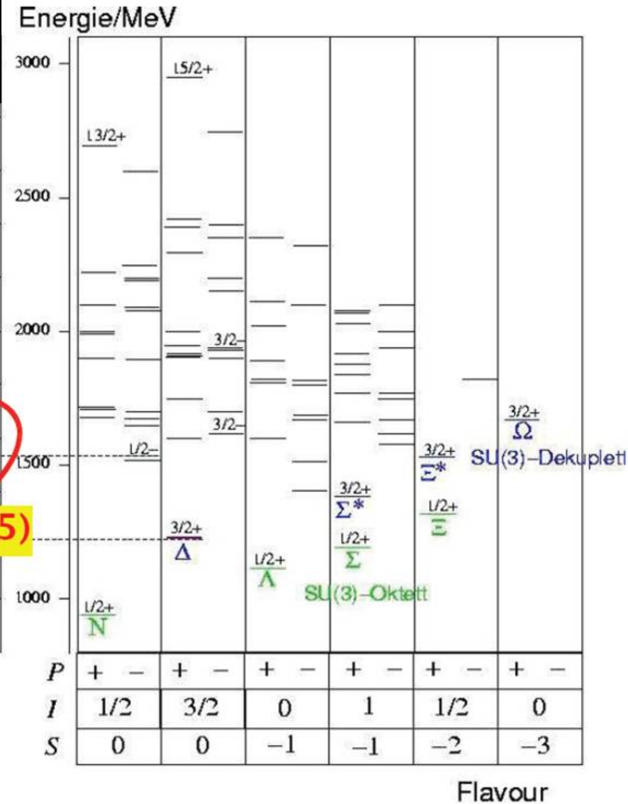
GW INS — Data Analysis Center — Institute for Nuclear Studies
THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC



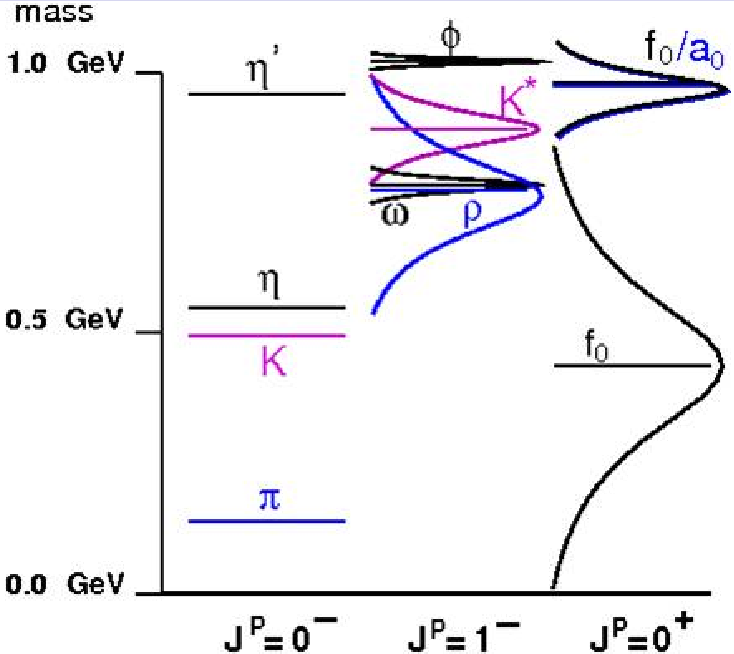
atom



nucleon

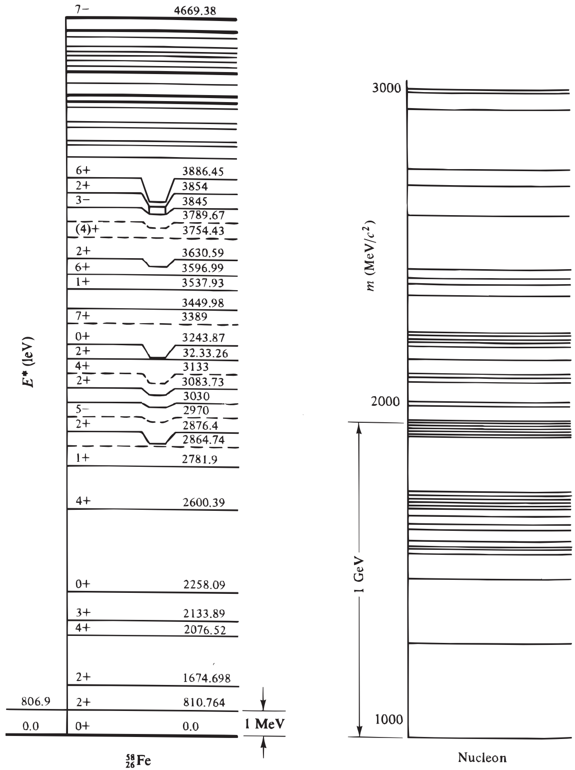


Results of the Standard Model: Meson Resonances



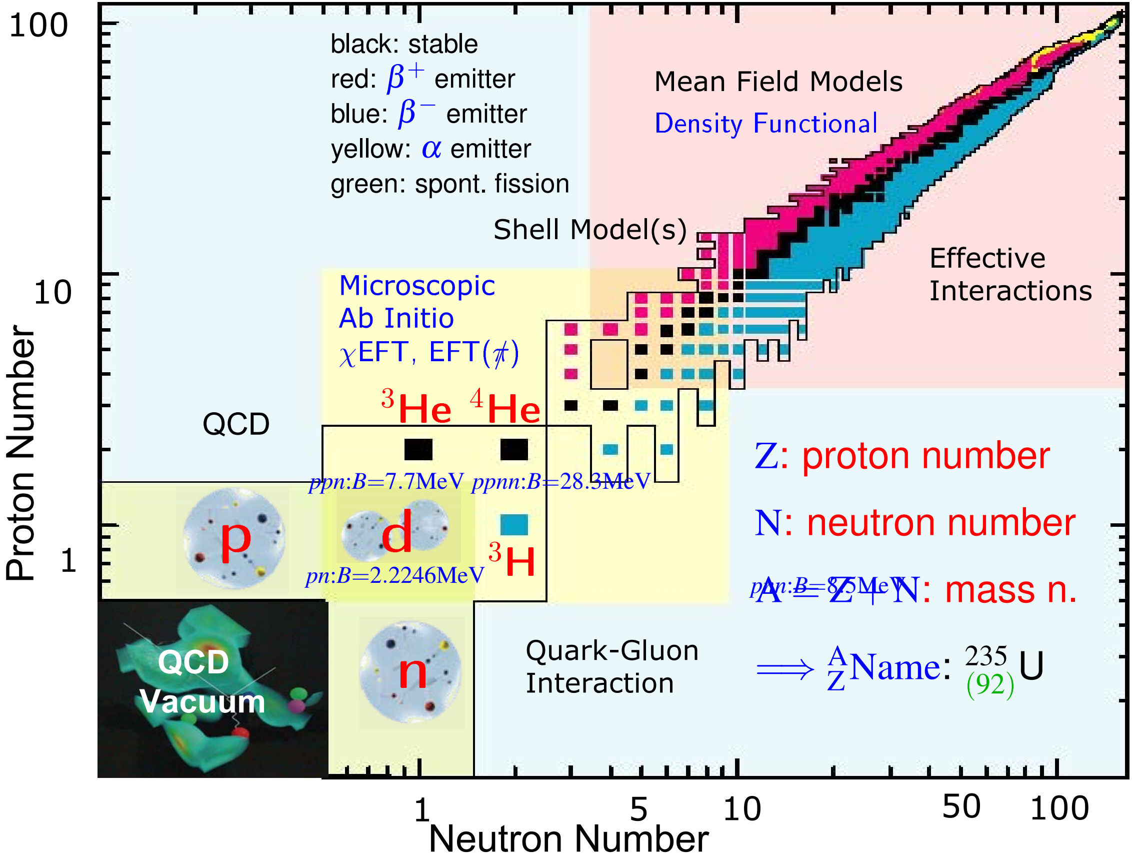
Vacuum Excitation Spectrum of the Standard Model

NucleAR Excitation Spectrum: Not Like H-Atom!

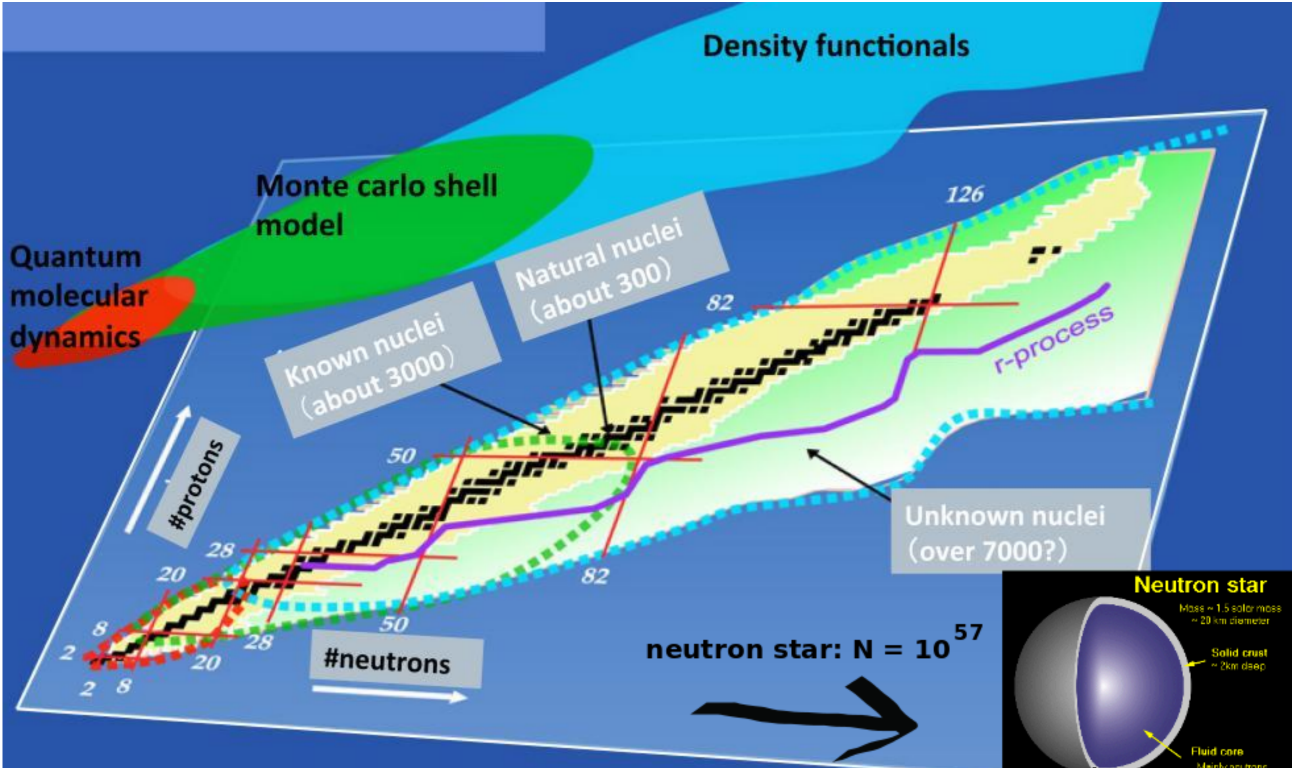


[HG fig. 5.37]

Results of the Standard Model: Nuclear Landscape



Know < 3000 nuclei (< 300 stable) – > 7000 unknown



need to account for gravity!

Explain Abundances of the Solar System!

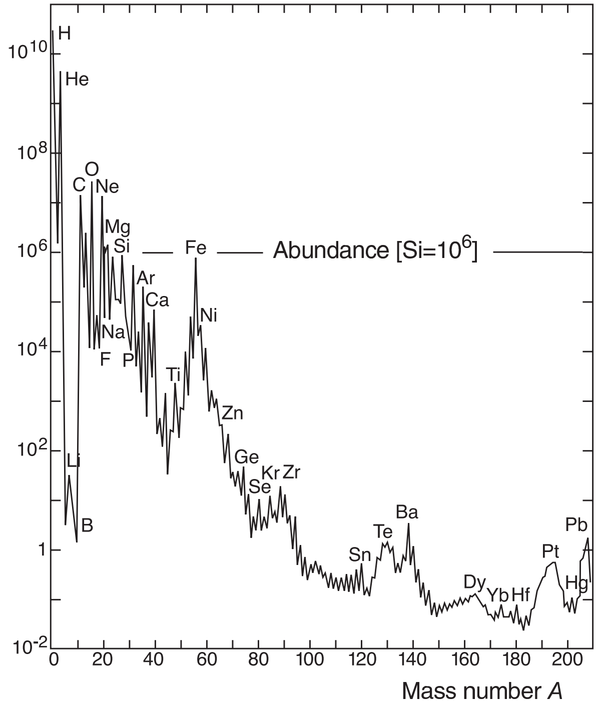
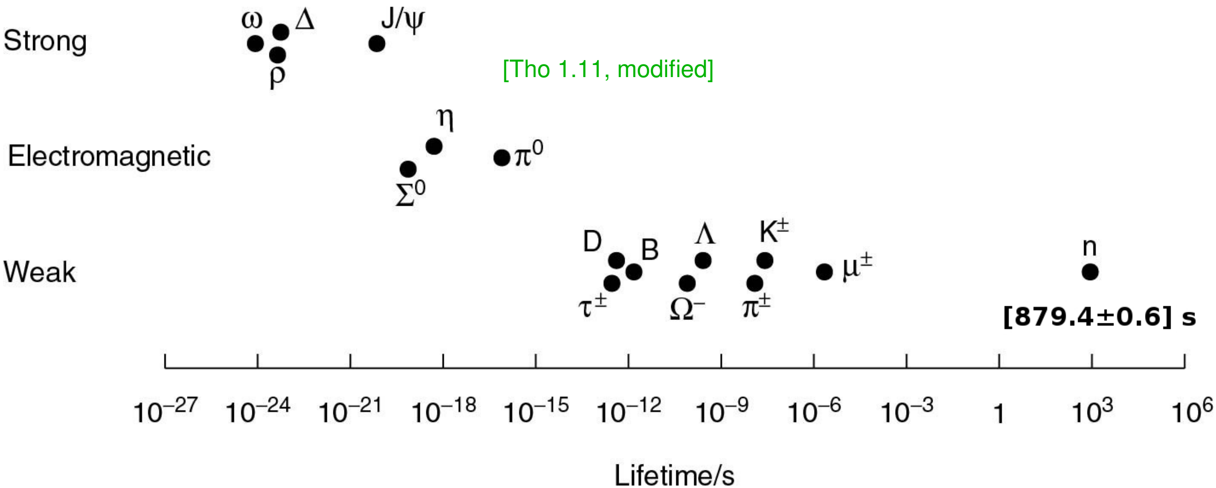


Fig. 2.2. Abundance of the elements in the solar system as a function of their mass number A, normalised to the abundance of silicon ($= 10^6$).

[PRSZR]

(f) Interactions: Patterns Emerging

Typical decay scales

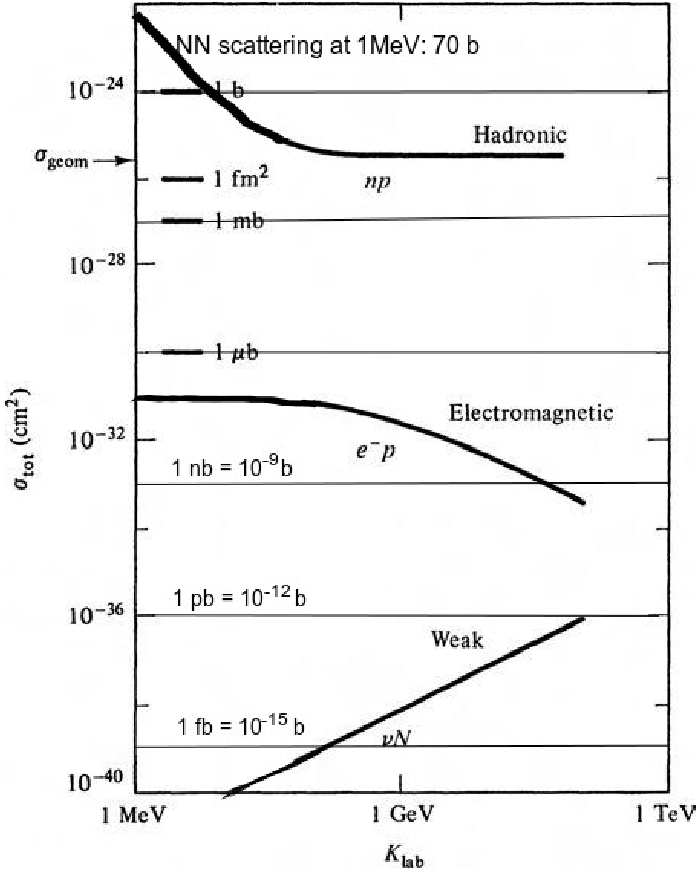


Minimum decay time for particle of size R: $\tau \geq \frac{R}{c}$: time to traverse object ("transmit signal to break up").

$$\Longrightarrow \tau_{\text{hadron}} \gtrsim \frac{1\text{ fm} = 10^{-15}\text{ m}}{c \approx 3 \times 10^{8}\text{ m s}^{-1}} \approx 10^{-24}\text{ s}$$ for "typical strong decay".

Nuclei show much more spread: 10^{-22}s to 10^{10}years – still depends on interaction.

Typical hadron cross sections



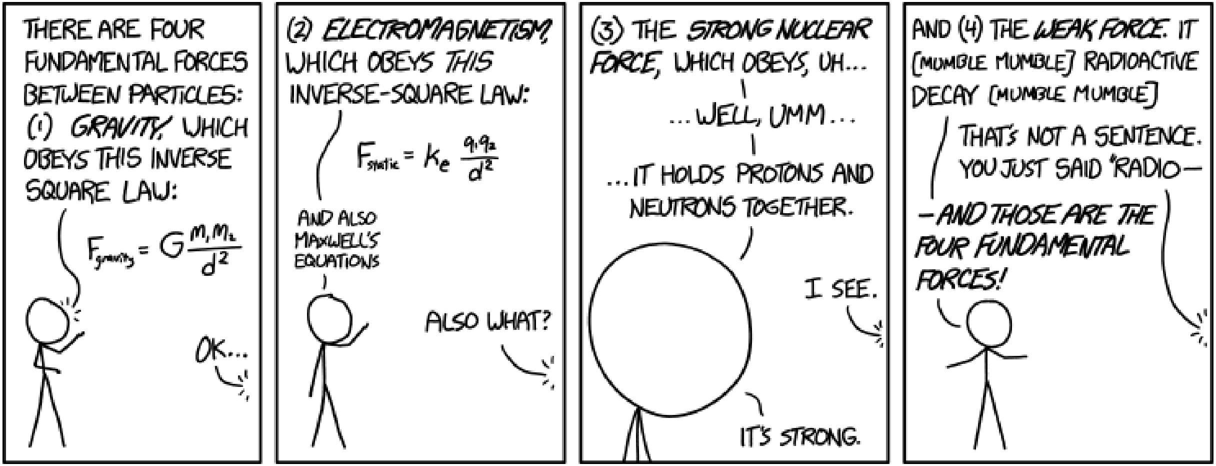
$\sim$ constant

decreases

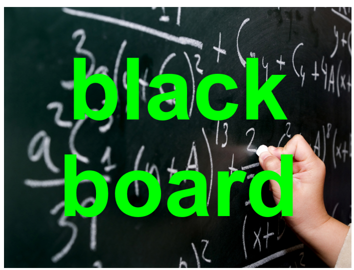
increases

[HG 14.2 modified]

(g) Interactions: Overview

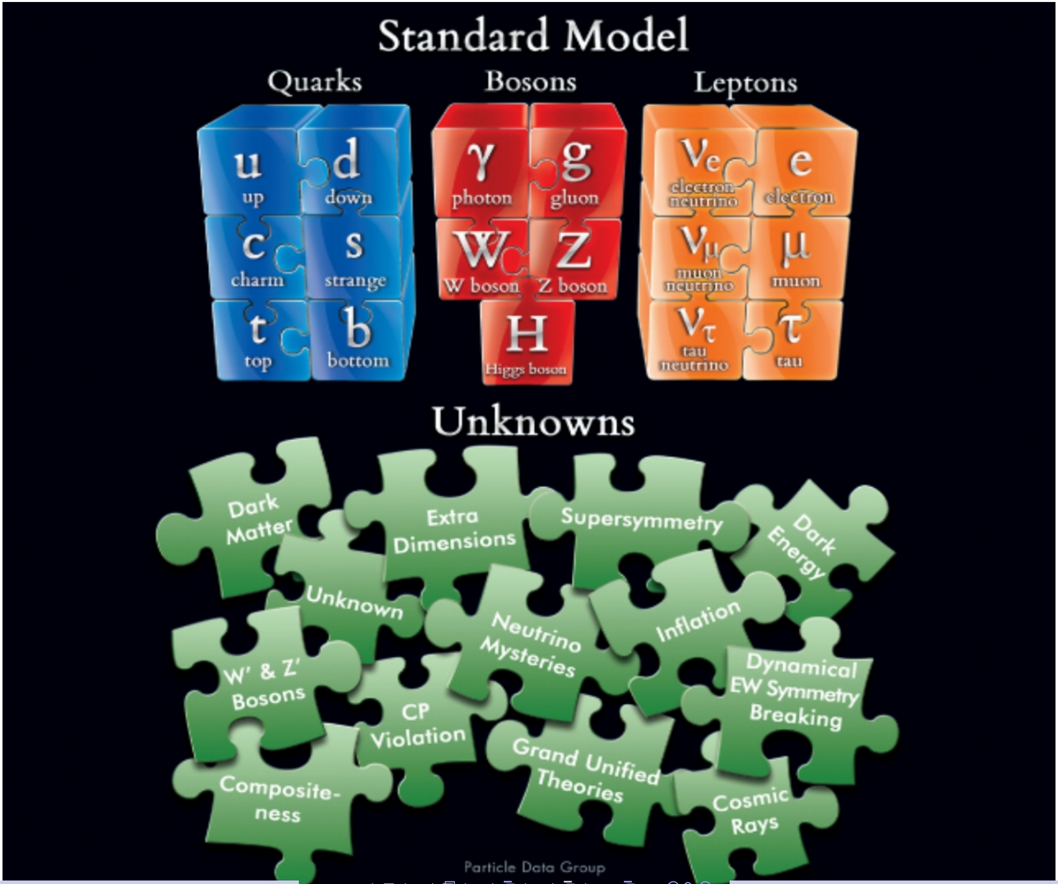


[xkcd 20 Feb 2015]



(weblink)

(h) The Known Unknowns: It's There, But What Is It?

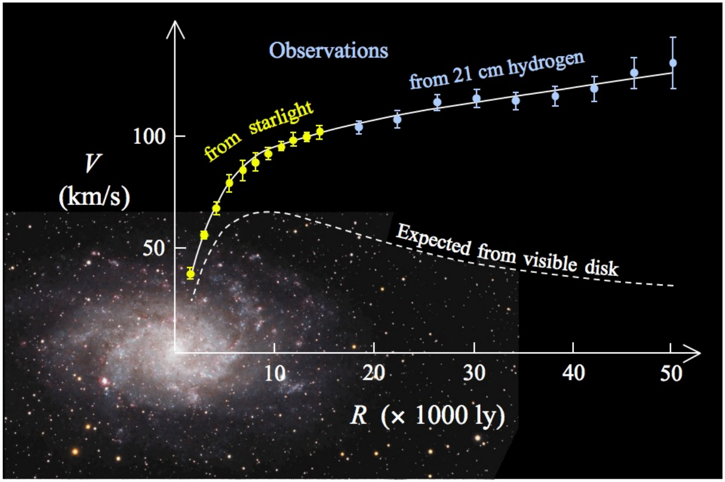


Dark Matter: known since 1922 (J. H. Jeans)

[PDG 27, Per 10.7]

Evidence: Velocity distribution of stars around galactic centres not explained by stars + gas

$\Longrightarrow$ "dark halo" of non-luminous/non-absorbing matter: **no interaction via electromagnetism**.



[wikipedia: Galaxy rotation curve]

More Evidence: Stronger in galactic clusters/superclusters; Cosmic Microwave Background Anisotropy

Preferred Candidates: **"Cold Dark Matter CDM"**: nonrelativistic (heavy!)

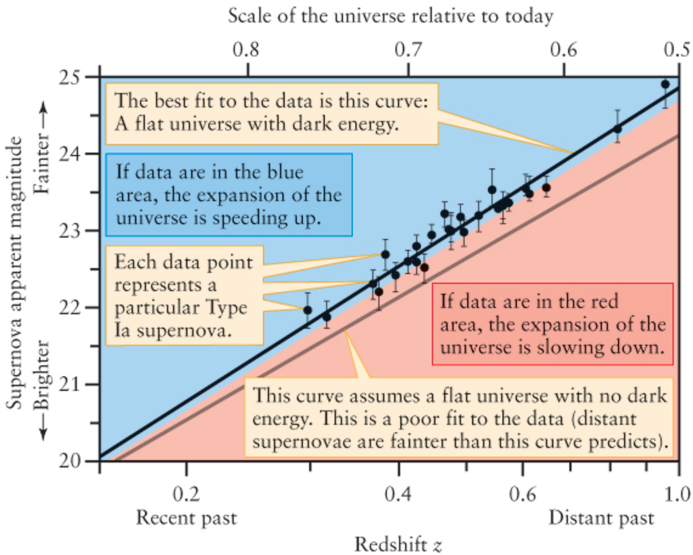
Some is baryonic (primordial black holes? Massive Compact Halo Objects **MACHO**s?);

≈ 80% *non-hadronic*: Weakly Interacting Massive Particles **WIMP**s (axions, SUSY, heavy neutrino,...)

Dark Energy: the accelerating universe [PDG 28]

Evidence: Redshift of type-Ia supernovae in Einstein-Friedman-Robertson-Walker universe:

Unknown long-range repulsive force counters gravity's pull. [Perlmutter/Schmidt/Riess 1998, Nobel 2011]



[scistand.com]

More Evidence: Cosmic Microwave Background Anisotropy.

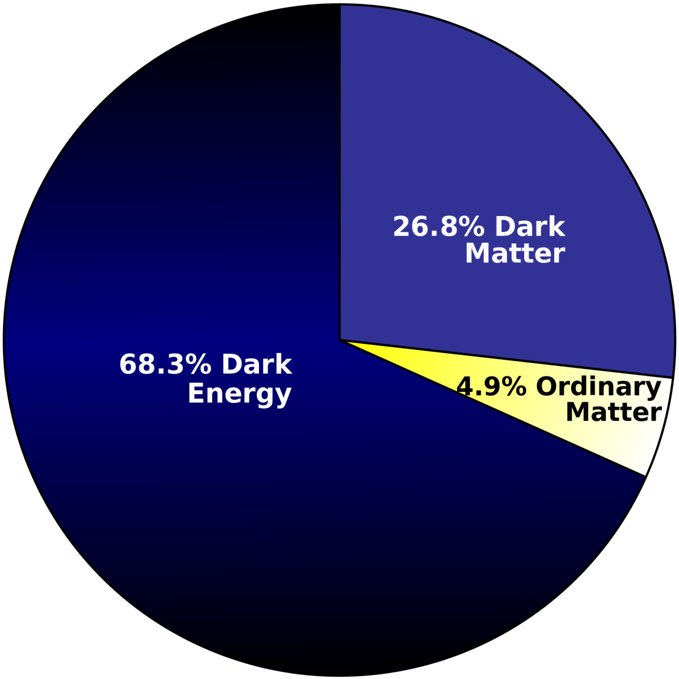
Preferred Candidates: Modified gravity at very large distance scales?;

Cosmological constant Λ (positive vacuum energy $\Longrightarrow$ negative pressure)?

Dark matter + dark energy $\Longrightarrow$ ΛCDM scenario

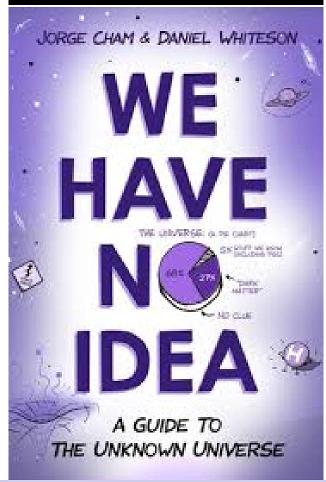
Matter content of the universe

We do not understand the composition of 95% of the universe.



mass generated by Higgs: $\lesssim 0.1\%$ (?)

[wikipedia: Dark energy]



Be wary of spectacular announcements

TIME Science

PHYSICS

Was Einstein Wrong? A Faster-than-Light Neutrino Could Be Saying Yes

By **MICHAEL D. LEMONICK** Friday, Sept. 23, 2011

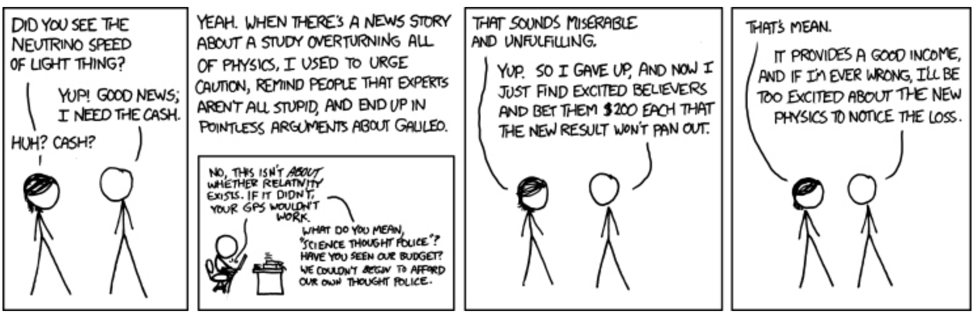
SUPERLUMINAL NEUTRINOS

Loose Cable May Unravel Faster-Than-Light Result

Anomalous data suggesting that neutrinos can travel faster than light probably resulted from a faulty connection in a GPS timing system, physicists from the OPERA collaboration revealed last week. Scientists who

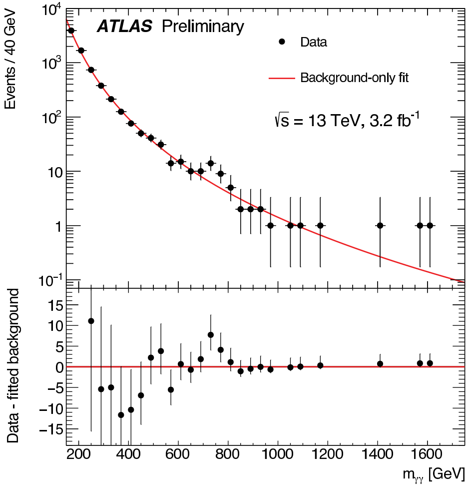
the coaxial fiber cable was plugged into a socket attached to a card inside the experiment's master-clock computer. The card converts the light pulses into electronic signals. Any loose connection was supposed to stop

[Science 335 (2 Mar 2012) 1027]



[xkcd]

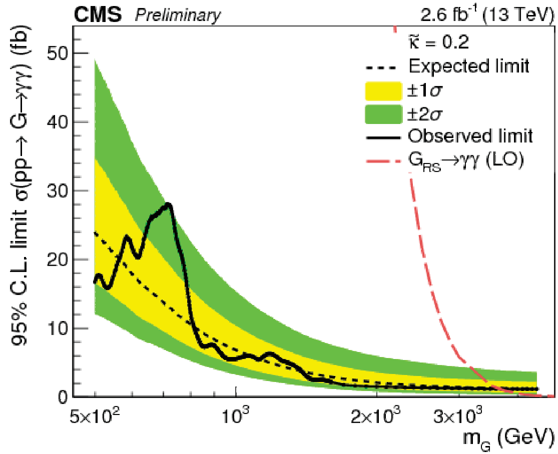
But hope springs eternal: a bump in $p\bar{p} \to \gamma\gamma$ at $M_X \approx 1.5$ TeV?



- **In the NWA search**, an excess of **3.6σ** (local) is observed at a mass hypothesis of minimal p_0 of 750 GeV

[ATLAS collaboration: CERN seminar 15 Dec 2015]

s

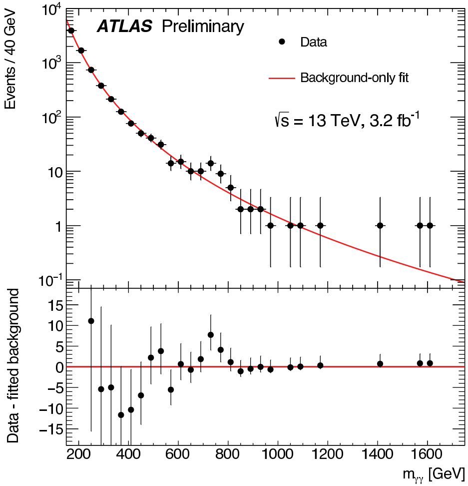


[CMS collaboration: CERN seminar 15 Dec 2015]

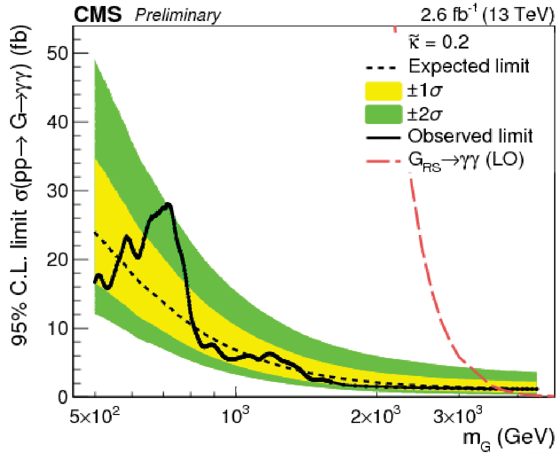
Statistics: Huge event number $\Longrightarrow$ fluctuations may mimic rare events.

Sagan's Rule: Extraordinary claims require extraordinary evidence.

But hope springs eternal: a bump in $p\bar{p} \to \gamma\gamma$ at $M_X \approx 1.5$ TeV?



S



- **In the NWA search**, an excess of **3.6σ** (local) is observed at a mass hypothesis of minimal p_0 of 750 GeV

[ATLAS collaboration: CERN seminar 15 Dec 2015]

[CMS collaboration: CERN seminar 15 Dec 2015]

Statistics: Huge event number $\Longrightarrow$ fluctuations may mimic rare events.

Sagan's Rule: Extraordinary claims require extraordinary evidence.

Wikipedia Jan 2018: Analysis of a larger sample of data, collected by ATLAS and CMS in the first half 2016, indicates that the excess seen in 2015 was a *statistical fluctuation*.

Next: 2. Particle Sources

Familiarise yourself with: [HG 2, 19.5; PDG 30, 31, 38]