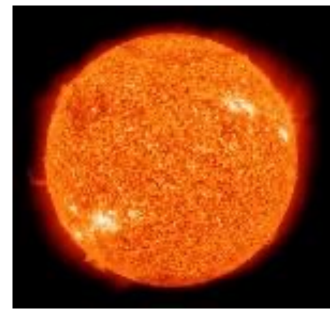
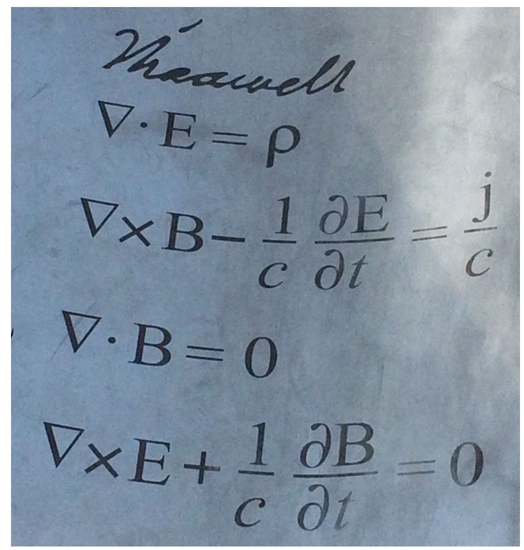
PARTICLE PHYSICS INTRODUCTION

Darin Acosta

The Fundamental Forces of Nature

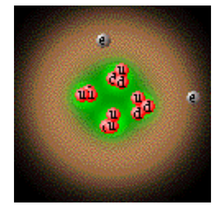


- Gravitation
  - The attractive force between objects with mass
    - Newton's Law of Gravitation $F = G\dfrac{m_1 m_2}{r^2}$
    - Einstein's General Theory of Relativity $G_{\mu\nu} = \dfrac{8\pi G}{c^4} T_{\mu\nu}$
- Electromagnetism
  - Electric force between electric charges
    - Coulomb's Law $F = \dfrac{q_1 q_2}{4\pi\varepsilon_0 r^2}$
  - Magnetic force between magnets and electric currents
    - Lorentz force law $\mathbf{F} = q(\mathbf{v} \times B)$
  - Unified in Maxwell's equations



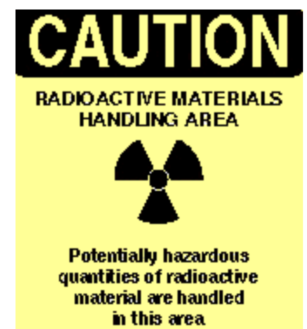
The Fundamental Forces of Nature

- Strong Nuclear Force
  - The force responsible for binding protons and neutrons in atomic nuclei
  - The binding energy is released in nuclear fission and fusion



- Weak Nuclear Force
  - The force responsible for radioactive decay (whereby one particle changes into another type)
  - For example the beta decay of a neutron

$$n \rightarrow p + e^{-} + \bar{\nu}_e$$



Approximate Ranking of Force Strengths

- Strong: 1
- $\lesssim 10^{-22}$ sec
- EM: 10^{-2}
- $\approx 10^{-16}$ sec
- Weak: 10^{-6}
- $\approx 10^{-10}$ sec
- Gravitation: 10^{-40}

The strength of the force generally governs the ***lifetime*** *of unstable particles, with an inverse relationship: stronger $\Rightarrow$ shorter lifetime*

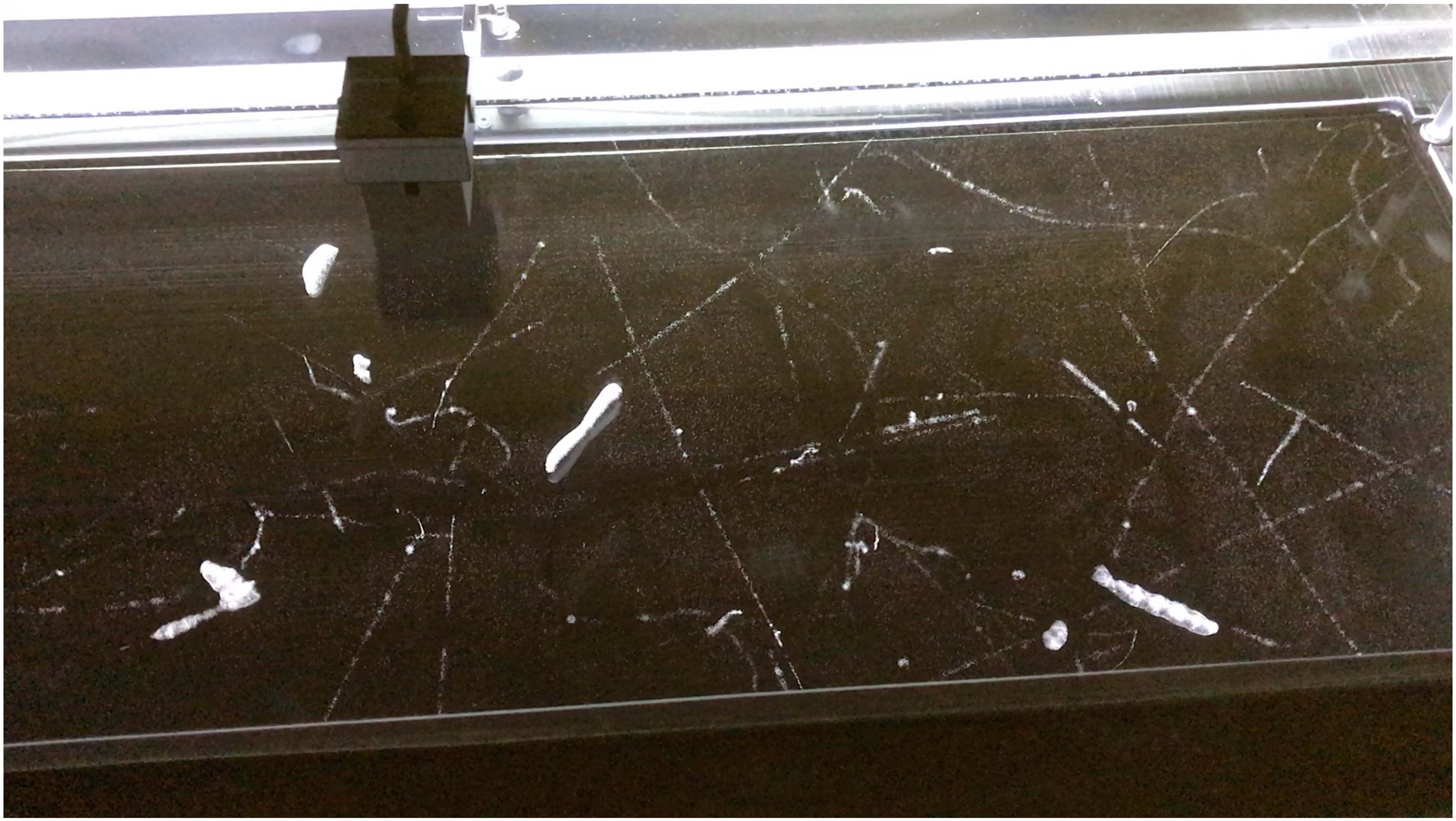
Depends also on the possible final states and "phase space"

Essentially the fine structure constant for each force

The Particle Zoo

- All stable matter is made of just 3 types of particles:
  - electrons, protons, and neutrons
- But with the advent of particle detectors and accelerators, many other types of particles have been discovered:
  - Muon, 1938, m=106 MeV
  - Pion, 1947, m=135 MeV
  - Kaon, rho, omega, …
  - Delta, Lambda, Sigma, Xi, …

Seeing Particles with a Cloud Chamber



See the listings from the Particle Data Group: http://pdg.lbl.gov

LIGHT UNFLAVORED MESONS (

Mini Reviews

Form Factors for Radiative Pion and I
Note on Scalar Mesons below 2 GeV
The $\rho(770)$
The Pseudoscalar and Pseudovector
The $\rho(1450)$ and $\rho(1700)$ (rev.)

Particles

$\pi^{\pm}$
π^0
η
$f_0(500)$or $\sigma$was $f_0(600)$
$\rho(770)$
$\omega(782)$
$\eta'(958)$
$f_0(980)$
$a_0(980)$
$\phi(1020)$
$h_1(1170)$
$b_1(1235)$
$a_1(1260)$
$f_2(1270)$
$f_1(1285)$
$\eta(1295)$
$\pi(1300)$
$a_2(1320)$
$f_0(1370)$
$h_1(1380)$
$\pi_1(1400)$
$\eta(1405)$
$f_1(1420)$
$\omega(1420)$
$f_2(1430)$
$a_0(1450)$
$\rho(1450)$
$\eta(1475)$

STRANGE MESONS (S = :

Mini Reviews

The Charged Kaon Mass
Rare Kaon Decays (rev.)
Dalitz Plot Parameters for K -
$K^{+-}_{\ell 3}$ and $K^0_{\ell 3}$ Form Factors
CPT Invariance Tests in Neu
CP Violation in $K^0_S \to 3\pi$
V_{ud}, V_{us} the Cabibbo Angle,
CP Violation in K^0_L Decays
$\Delta S = \Delta Q$ in K^0 Decays
$K^*(892)$ Masses and Mass [

Particles

$K^{\pm}$
K^0
K^0_S
K^0_L
$K^*_0(800)$or κ
$K^*(892)$
$K_1(1270)$
$K_1(1400)$
$K^*(1410)$
$K^*_0(1430)$
$K^*_2(1430)$
$K(1460)$
$K_2(1580)$
$K(1630)$
$K_1(1650)$
$K^*(1680)$
$K_2(1770)$
$K^*_3(1780)$
$K_2(1820)$
$K(1830)$
$K^*_0(1950)$
$K^*_2(1980)$
$K^*_4(2045)$

CHARMED MESONS (

Mini Reviews

$D^0 - \overline{D}^0$ Mixing (rev.)

Particles

$D^{\pm}$
D^0
$D^*(2007)^0$
$D^*(2010)^{\pm}$
$D^*_0(2400)^0$
$D^*_0(2400)^{\pm}$
$D_1(2420)^0$
$D_1(2420)^{\pm}$
$D_1(2430)^0$
$D^*_2(2460)^0$
$D^*_2(2460)^{\pm}$
$D(2550)^0$
$D^*_J(2600)$was $D(260($
$D^*(2640)^{\pm}$
$D(2740)^0$
$D(2750)$
$D(3000)^0$

BOTTOM MESONS ($B = \pm 1$)

Mini Reviews

Production and Decay of b-flavored Hadrons
A Note on HFAG Activities (rev.)
Polarization in B Decays (rev.)
$B^0 - \overline{B}^0$ Mixing (rev.)
Semileptonic B meson decays and the determination of V_{cb} and V_{ub} (rev.)

Particles

B-particle organization
$B^{\pm}$
B^0
$B^{\pm}/B^0$ ADMIXTURE
$B^{\pm}/B^0/B^0_s/b$-baryon ADMIXTURE
V_{cb} and V_{ub} CKM Matrix Elements
B^*
$B_1(5721)^+$ **
$B_1(5721)^0$ ***
$B^*_J(5732)$or B^{**}
$B^*_2(5747)^+$ **
$B^*_2(5747)^0$ ***
$B_J(5840)^+$ **
$B_J(5840)^0$ **
$B_J(5970)^+$ **
$B_J(5970)^0$ **

See the listings from the Particle Data Group: http://pdg.lbl.gov

N BARYONS (S = 0, I

Mini Reviews

Baryon Decay Paramet
N and Δ Resonances (

Particles

p
n
$N(1440)\ 1/2^+$
$N(1520)\ 3/2^-$
$N(1535)\ 1/2^-$
$N(1650)\ 1/2^-$
$N(1675)\ 5/2^-$
$N(1680)\ 5/2^+$
$N(1700)\ 3/2^-$
$N(1710)\ 1/2^+$
$N(1720)\ 3/2^+$
$N(1860)\ 5/2^+$
$N(1875)\ 3/2^-$
$N(1880)\ 1/2^+$
$N(1895)\ 1/2^-$
$N(1900)\ 3/2^+$
$N(1990)\ 7/2^+$
$N(2000)\ 5/2^+$
$N(2040)\ 3/2^+$
$N(2060)\ 5/2^-$

Δ BARYONS (S = 0

Particles

$\Delta(1232)\ 3/2^+$
$\Delta(1600)\ 3/2^+$
$\Delta(1620)\ 1/2^-$
$\Delta(1700)\ 3/2^-$
$\Delta(1750)\ 1/2^+$
$\Delta(1900)\ 1/2^-$
$\Delta(1905)\ 5/2^+$
$\Delta(1910)\ 1/2^+$
$\Delta(1920)\ 3/2^+$
$\Delta(1930)\ 5/2^-$
$\Delta(1940)\ 3/2^-$
$\Delta(1950)\ 7/2^+$
$\Delta(2000)\ 5/2^+$
$\Delta(2150)\ 1/2^-$
$\Delta(2200)\ 7/2^-$
$\Delta(2300)\ 9/2^+$
$\Delta(2350)\ 5/2^-$
$\Delta(2390)\ 7/2^+$
$\Delta(2400)\ 9/2^-$
$\Delta(2420)\ 11/2^+$
$\Delta(2750)\ 13/2^-$
$\Delta(2950)\ 15/2^+$
$\Delta(\sim 3000$ Region)

Λ BARYONS (S =

Mini Reviews

Baryon Magnetic Mo
Λ and Σ Resonance
Λ and Σ Resonance

Particles

Λ
$\Lambda(1405)\ 1/2^-$
$\Lambda(1520)\ 3/2^-$
$\Lambda(1600)\ 1/2^+$
$\Lambda(1670)\ 1/2^-$
$\Lambda(1690)\ 3/2^-$
$\Lambda(1710)\ 1/2^+$
$\Lambda(1800)\ 1/2^-$
$\Lambda(1810)\ 1/2^+$
$\Lambda(1820)\ 5/2^+$
$\Lambda(1830)\ 5/2^-$
$\Lambda(1890)\ 3/2^+$
$\Lambda(2000)$
$\Lambda(2020)\ 7/2^+$
$\Lambda(2050)\ 3/2^-$
$\Lambda(2100)\ 7/2^-$
$\Lambda(2110)\ 5/2^+$
$\Lambda(2325)\ 3/2^-$

Σ BARYONS ($S = -1, I = 1$)

Mini Reviews

The $\Sigma(1670)$ Region

Particles

Σ^+	****
Σ^0	****
Σ^-	****
$\Sigma(1385)\ 3/2^+$	****
$\Sigma(1480)$ Bumps	*
$\Sigma(1560)$ Bumps	**
$\Sigma(1580)\ 3/2^-$	*
$\Sigma(1620)\ 1/2^-$	*
$\Sigma(1620)$ Production Experiments	
$\Sigma(1660)\ 1/2^+$	***
$\Sigma(1670)\ 3/2^-$	****
$\Sigma(1670)$ Bumps	
$\Sigma(1690)$ Bumps	**
$\Sigma(1730)\ 3/2^+$	*
$\Sigma(1750)\ 1/2^-$	***
$\Sigma(1770)\ 1/2^+$	*
$\Sigma(1775)\ 5/2^-$	****
$\Sigma(1840)\ 3/2^+$	*
$\Sigma(1880)\ 1/2^+$	**
$\Sigma(1900)\ 1/2^-$	*
$\Sigma(1915)\ 5/2^+$	****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ANTIMATTER
FACTORY
ELENA
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Particle Classification

- Hadrons:
  - Particles that interact with the strong nuclear force (carry nuclear charge)
    - Baryons:
      - Fermions (spin = 1/2, 3/2, 5/2, …)
      - Includes the nucleons (p, n) and excitations of them (Δ, Λ, …)
    - Mesons:
      - Bosons (spin = 0, 1, 2, …)
      - π, K, ρ, ω, …
      - Typically lighter than baryons (except when containing heavy quarks)

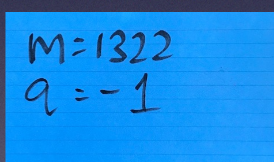
Not fundamental

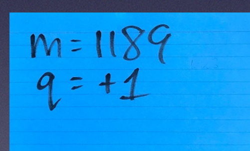
- Leptons:
  - Particles that do not interact with the strong nuclear force (do not bind in nuclei)
    - All spin ½ fermions
      - Charged leptons: $e^{\pm}$, $\mu^{\pm}$, $\tau^{\pm}$
      - Electrically neutral leptons: ν_e, ν_μ, ν_τ

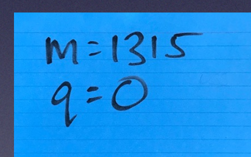
Fundamental (point-like) as far as we know

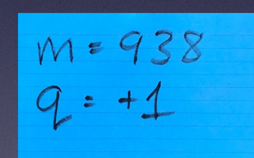
“Eightfold Way” Activity

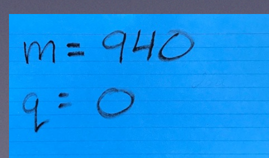
- Let’s retrace the historical reasoning by Murray Gell-Mann
    - The following cards list only the mass and charge of specific particle
    - Can you see any patterns after organizing by charge and mass?

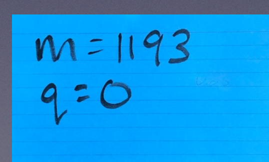


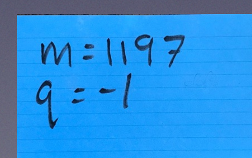






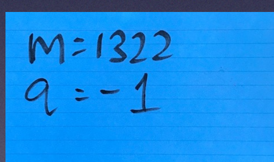


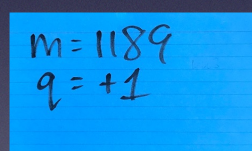


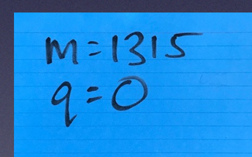


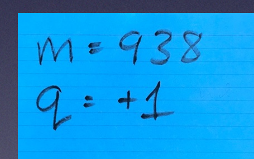
Mass is in units of MeV, charge in proton units

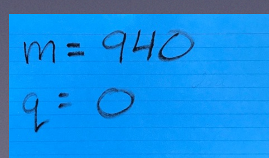
“Eightfold Way” Activity

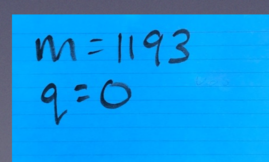


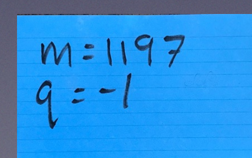












Mass is in units of MeV, charge in proton units

“Eightfold Way” Activity

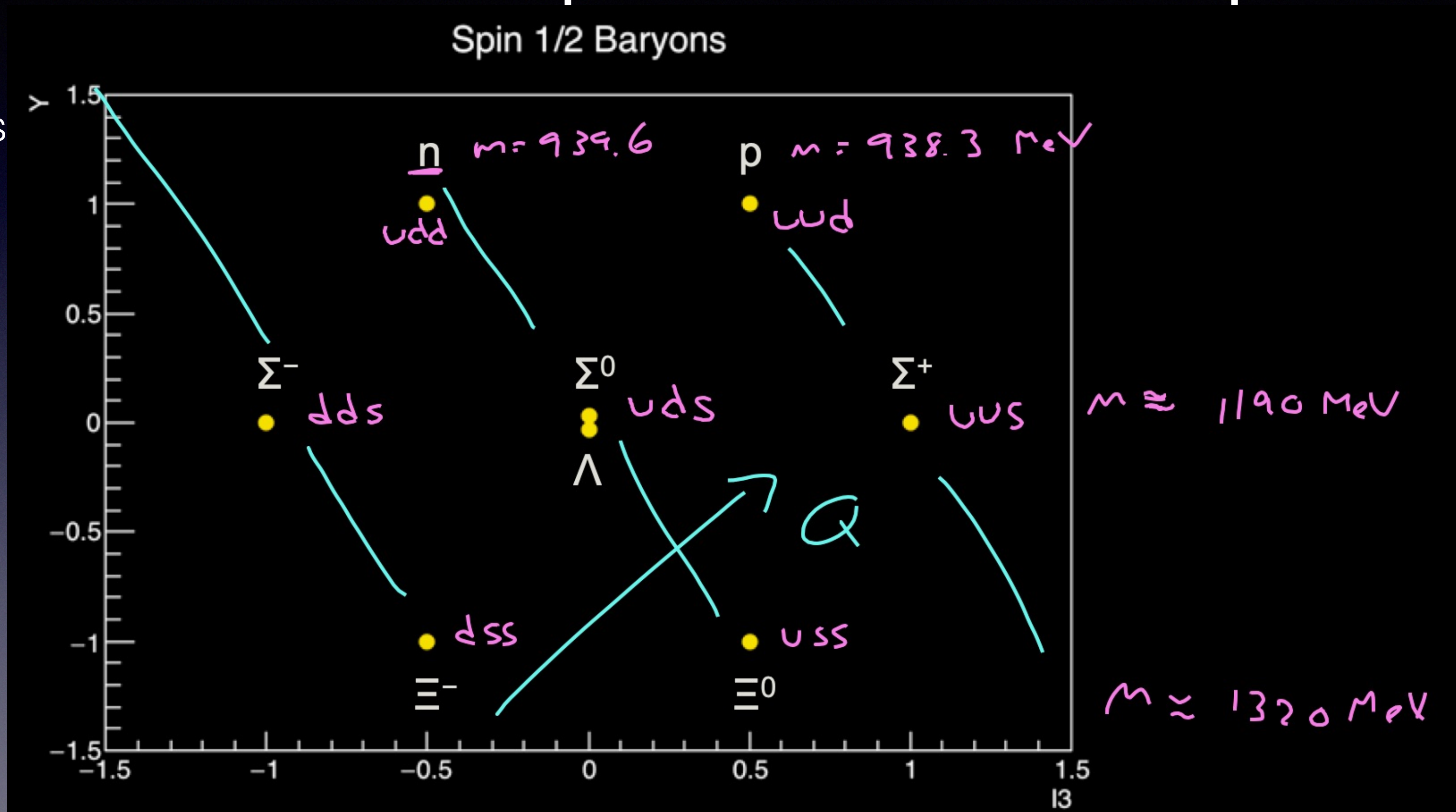
- Now suppose each card represents a bound state of 3 particles taken from this list of 3 new fundamental particles:
- u: electric charge = +2/3 e
- d: electric charge = −1/3 e
- s: electric charge = −1/3 e
  (and s is heavier than u or d)

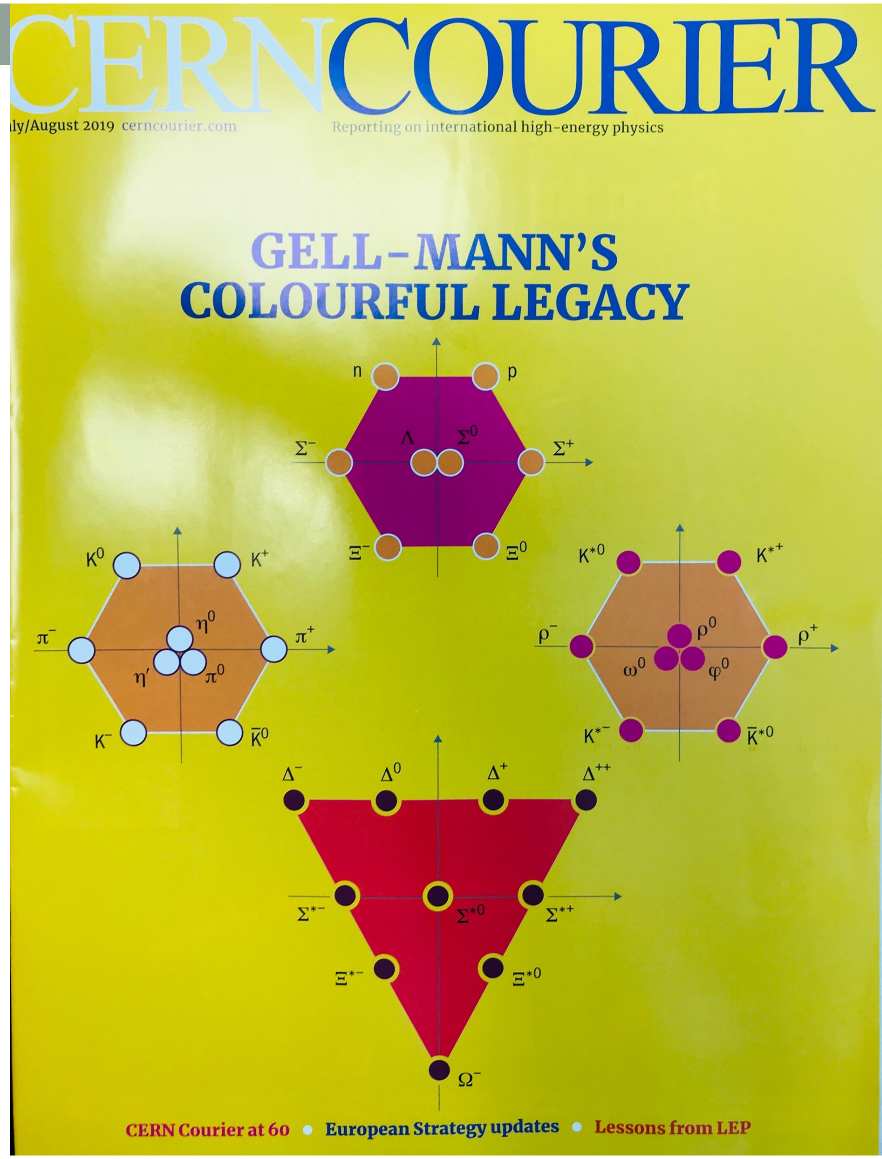
Patterns describe particle “multiplets”

Suggests particles comprised of 3 constituent “quarks”: u, d, s

electric charge 2/3, -1/3, -1/3

s is heavier

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Σ⁻
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K*⁰
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Σ*⁻
Σ*⁰
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Ξ*⁻
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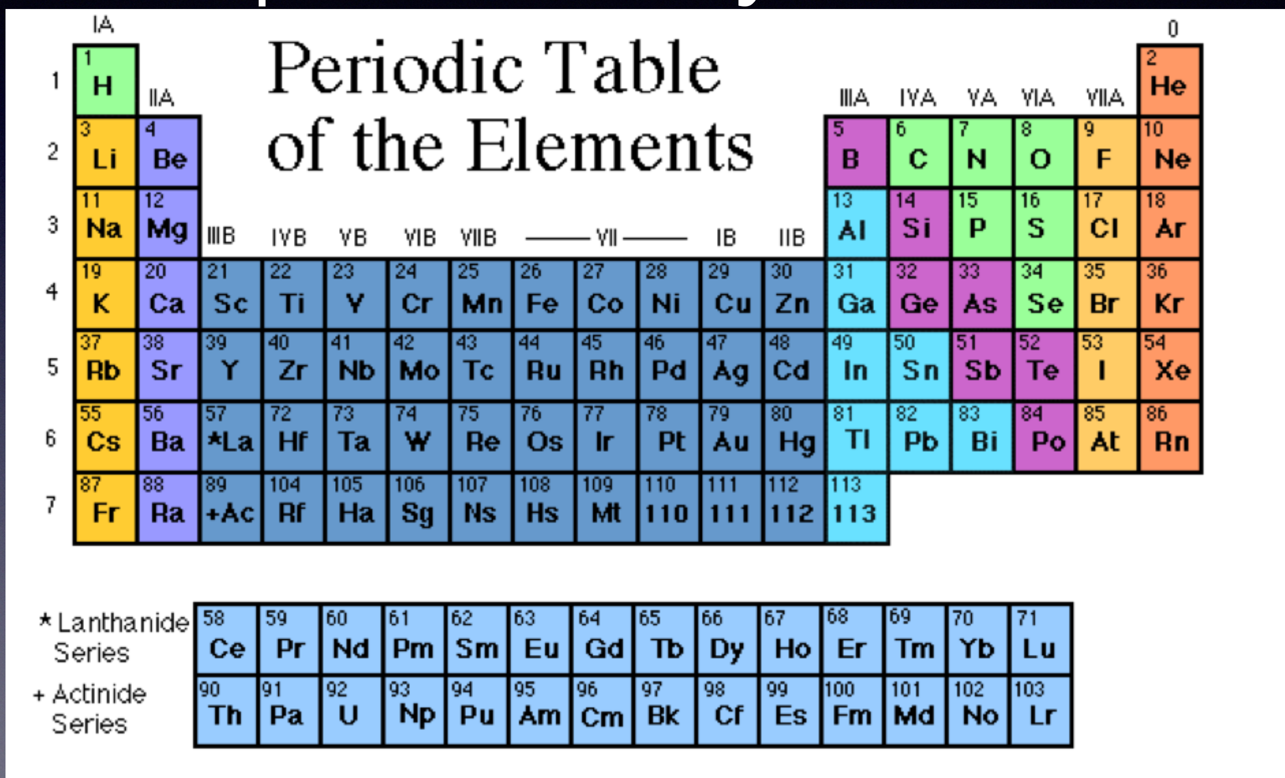
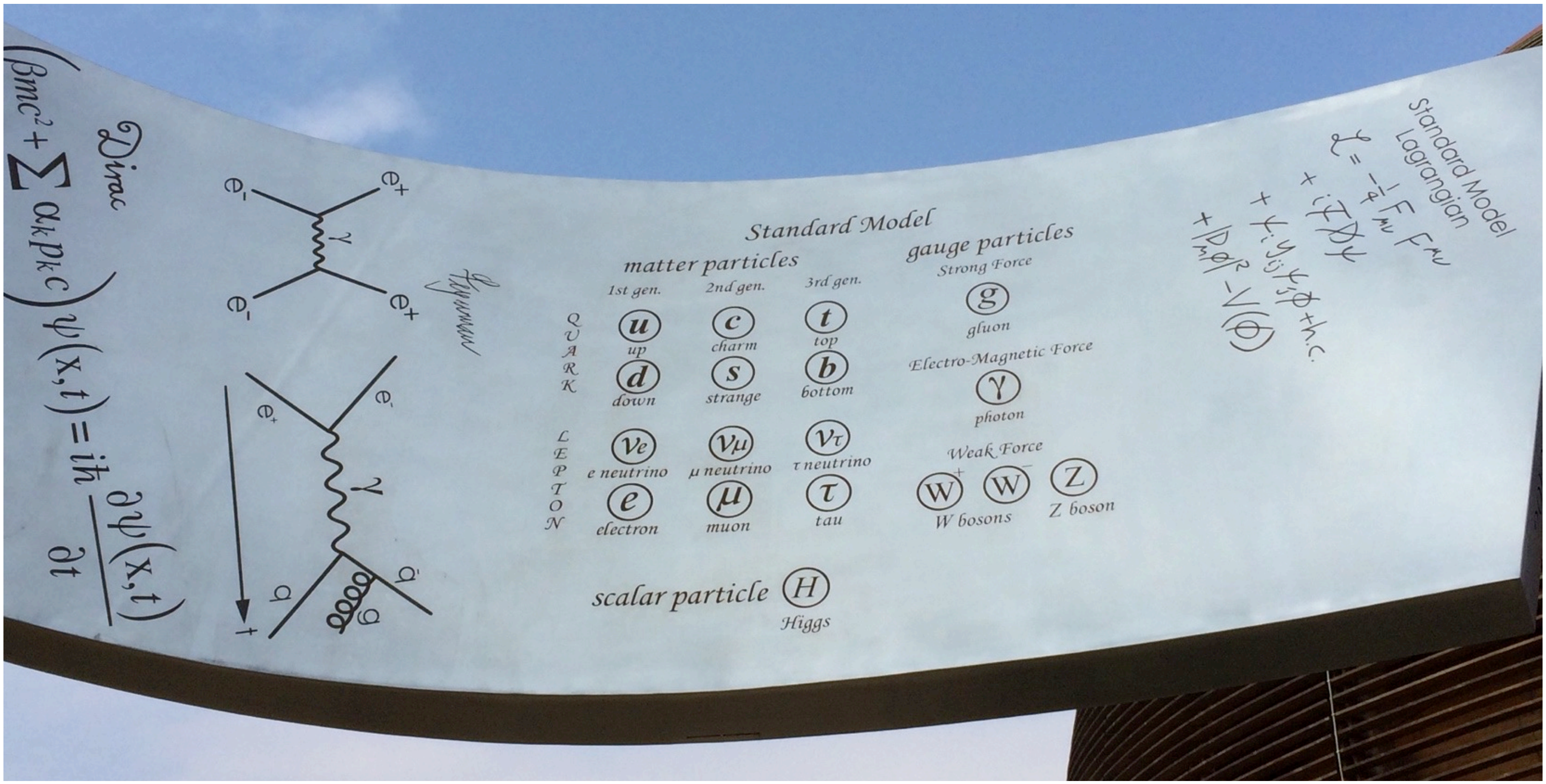
Zoo of known elements/particles explained by a few constituents



- Building **composite particles** out of subatomic quarks is quite **analogous** to **building atoms** out of protons, neutrons, and electrons

The Standard Model



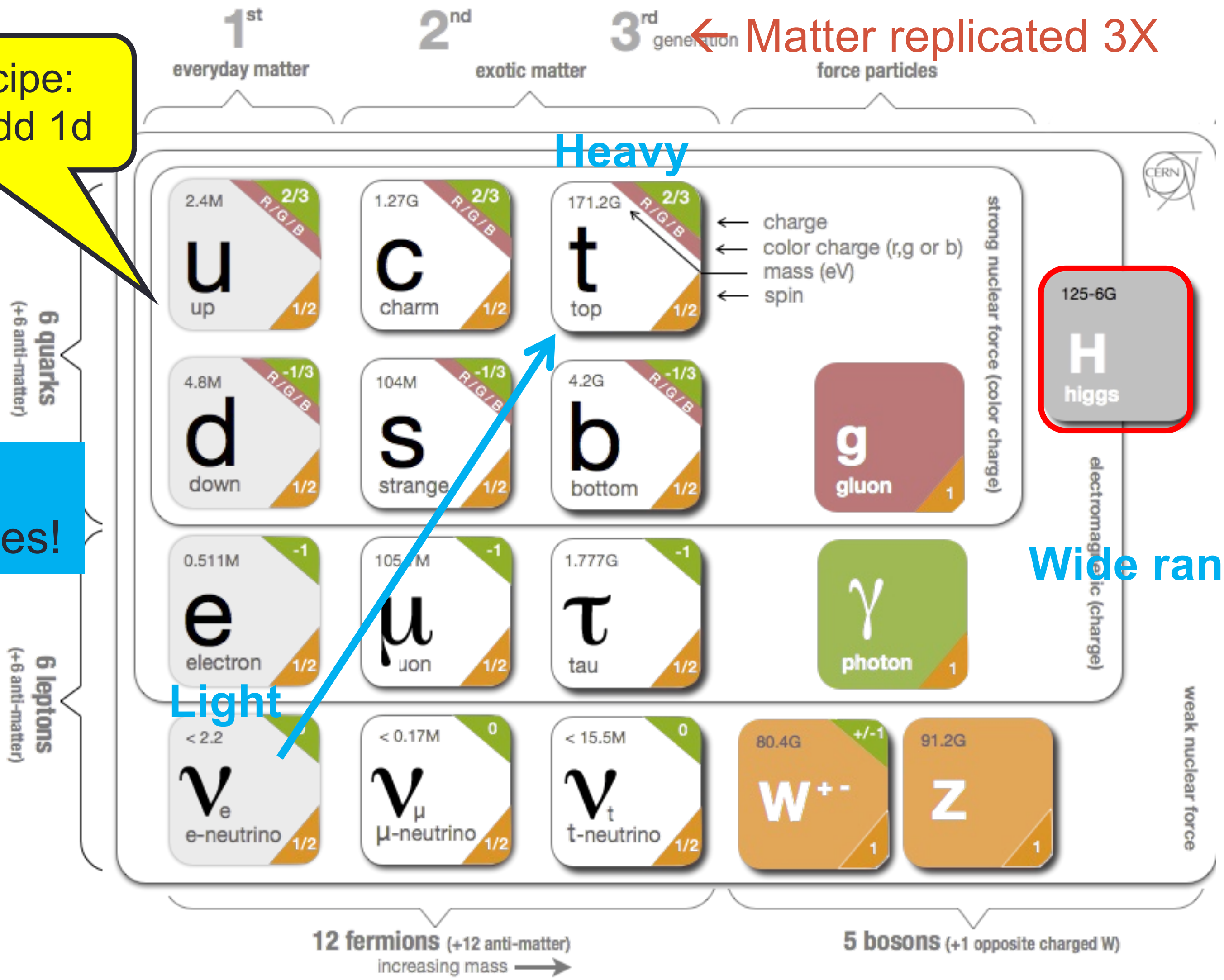
Proton recipe: Take 2u, add 1d

← Matter replicated 3X

Quarks

And their anti-particles!

Leptons



Discovered 2012!

Wide range of masses

Force carrying particles (gauge bosons)