Puzzles for Particle Physics

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Physics 301: Physics Today
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Why Particles?

- Electromagnetic
- Weak
- Strong
Why Particles?
Particles of the Standard Model
History of Particle Discovery

The Standard Model of particle physics
Years from concept to discovery

Electron
Photon
Muon
Electron neutrino
Muon neutrino
Down
Strange
Up
Charm
Tau
Bottom
Gluon
W boson
Z boson
Top
Tau neutrino
HIGGS BOSON

Source: The Economist
Why We Need the Higgs Boson?

otherwise, the unitary is violated (the sum of probability is not 100%)
Higgs Potential

\[ V(\phi) = \frac{1}{2} \mu^2 \phi^\dagger \phi + \frac{1}{4} \lambda (\phi^\dagger \phi)^2 \]

Groundstate at \[ |\phi_0| = \sqrt{\frac{-\mu^2}{\lambda}} \equiv v \]

\[ |\phi| = \sqrt{\phi^\dagger \phi} = \sqrt{\phi^* \phi + \phi^0 \phi^0} \]

\[ V(\phi_0) = -\frac{\lambda}{4} v^4 \]
Other Vacuum at Quantum Level
CAUTION: ±3 GeV theory uncertainty.

$m_h = 124$ GeV

$m_t = 173.2$ GeV

$\alpha_3(M_Z) = 0.1184$

$m_t = 171.4$ GeV

$\alpha_3(M_Z) = 0.1198$

$m_t = 175.0$ GeV

$\alpha_3(M_Z) = 0.117$

$\lambda_3 h M Z L = 0.1184$

$\lambda_3 h M Z L = 0.117$

$\lambda_3 h M Z L = 0.1198$

$\lambda_3 h M Z L = 0.1198$

$\lambda_3 h M Z L = 0.117$

$\lambda_3 h M Z L = 0.117$
We are in a Meta-Stable Vacuum

Puzzles

1. Fermion Yukawa couplings

\[ \frac{m_e}{m_t} = 10^{-6} \]

2. Hierarchy problem

\[ \frac{v_{\text{EW}}}{M_{\text{Pl}}} = 10^{-16} \]

3. Baryon and anti-baryon number asymmetry

\[ \frac{n_B - n_{\bar{B}}}{n_B + n_{\bar{B}}} = 10^{-10} \]

4. Dark matter

\[ \frac{\Omega_{\text{DM}}}{\Omega_{\text{Baryon}}} = 5 \]

5. Cosmological constant problem

\[ \frac{\Lambda}{M_{\text{Pl}}^4} = 10^{-120} \]
Puzzle 1: Fermion masses and mixing

Image credit: Gordon Kane, Scientific American, June 2003
Puzzle 1: Fermion masses and mixing

Is the pattern associated with some underlying symmetry, just like our SM has

$$SU(3)_{QCD} \times SU(2)_W \times U(1)_Y$$

How about SU(3)\_flavor global symmetry?

Why lepton and quark sectors have different mixing structures?

Is the relation $\theta_{12}^{\text{CKM}} + \theta_{12}^{\text{PMNS}} \approx \frac{\pi}{2}$ accidental?

What is the flavor breaking scale? Can we test them?
Puzzle 2: Hierarchy Problem

How can we have a stable electroweak scale from the theory point of view?

\[
\frac{v_{EW}}{M_{Pl}} = 10^{-16}
\]

\[
V = m_H^2 |H|^2 + \lambda |H|^4
\]

\[
\Delta m_H^2 = -\frac{\lambda f^2}{8\pi^2} \Lambda_{UV}^2 + \ldots
\]
Supersymmetry explanation:

\[ \Delta(m_{h^0}^2) = h^0 + h^0 + \tilde{t} + h^0 \]

the new particle can not be too heavy and should be found in the near future.
Puzzle 2: Hierarchy Problem

We have not found it yet. You can contribute a new explanation different from SUSY.
Puzzle 3: Baryon-anti-baryon Assym.

Image Credit: Hitoshi Murayama
Puzzle 3: Baryon-antibaryon Assym.

Our Standard Model does not have enough CP violation. New complex phases should appear.

People are measuring CPv in the neutrino sector, although it may not really help.
Puzzle 4: Dark Matter

Image Credit: NASA/Swift Science Team/Stefan Immler
Newton’s law

The physics law works independent of whether you can see the M matter or not
Using the Doppler shift, we can measure the galaxy ‘rotation curve’ $v(R)$.

Assuming all the mass of galaxies come from the region where stars are visible.

From Kepler’s law, we expect

$$v \sim \frac{1}{\sqrt{R}}$$
Galaxy Rotation Curve

Missing matter exists beyond the visible star region
Here are rotation curves for more galaxies

Sofue and Rubin
More Evidence

Gravitational Lensing
More Evidence

Image Credit: Chandra X-ray observatory
Quantitatively, we have the energy pie of our universe from PLANCK.
and the *matter* pie of our universe

- Ordinary Matter: 15.5%
- Dark Matter: 84.5%

*from PLANCK*
molecular, atom, electron, nucleus, proton, neutron, quarks

**Standard Model**

<table>
<thead>
<tr>
<th>Bosons</th>
<th>Name</th>
<th>Mass GeV/c²</th>
<th>Electric Charge</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Photon</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>$W^-$</td>
<td>80.39</td>
<td>-1</td>
</tr>
<tr>
<td></td>
<td>$W^+$</td>
<td>80.39</td>
<td>+1</td>
</tr>
<tr>
<td></td>
<td>$Z^0$</td>
<td>91.188</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Higgs</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Allowed Electroweak** spin = 1
- **Strong (color)** spin = 1

**Higgs**

**Electroweak Symmetry Breaking**

**Dark Matter Sector ???**

<table>
<thead>
<tr>
<th>Fermions</th>
<th>Flavor</th>
<th>Mass GeV/c²</th>
<th>Electric Charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leptons</td>
<td>$\nu_e$</td>
<td>(0 – 0.13)×10⁻⁹</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>$e^+$</td>
<td>0.000511</td>
<td>-1</td>
</tr>
<tr>
<td></td>
<td>$\nu_{\mu}$</td>
<td>(0.009–0.13)×10⁻⁹</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>$\mu^+$</td>
<td>0.106</td>
<td>-1</td>
</tr>
<tr>
<td></td>
<td>$\nu_{\tau}$</td>
<td>(0.04–0.14)×10⁻⁹</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>$\tau^+$</td>
<td>1.777</td>
<td>-1</td>
</tr>
</tbody>
</table>

**Quarks**

- Matter constituents
- spin = 1/2, 3/2, 5/2, ...

<table>
<thead>
<tr>
<th>Flavor</th>
<th>Approx. Mass GeV/c²</th>
<th>Electric Charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u$</td>
<td>0.002</td>
<td>2/3</td>
</tr>
<tr>
<td>$d$</td>
<td>0.005</td>
<td>-1/3</td>
</tr>
<tr>
<td>$c$</td>
<td>1.3</td>
<td>2/3</td>
</tr>
<tr>
<td>$s$</td>
<td>0.1</td>
<td>-1/3</td>
</tr>
<tr>
<td>$t$</td>
<td>173</td>
<td>2/3</td>
</tr>
<tr>
<td>$b$</td>
<td>4.2</td>
<td>-1/3</td>
</tr>
</tbody>
</table>
All evidence only requires the gravitational interaction between dark matter and ordinary matter

Why we care about its additional interactions?

• We don’t know its properties. For ordinary matter, we understand their particle properties

• It is non-trivial to have

\[
\begin{align*}
\text{Dark Matter} & \quad (84.5\%) \\
\text{Ordinary Matter} & \quad (15.5\%) \\
\hline
= & \quad 5.45
\end{align*}
\]
Quantitatively, solving the Boltzmann equation for the WIMP density, we have

$$\Omega_\chi = \frac{s_0}{\rho_c} \left( \frac{45}{\pi g_*} \right)^{1/2} \frac{x_f \frac{1}{m_{pl}}}{\langle \sigma v \rangle}$$

Putting in the numbers:

$$\langle \sigma v \rangle \approx 1 \text{ pb} \approx \frac{\pi \alpha^2}{8m^2_\chi}$$

for $m_\chi = 100$ GeV

This points to the length scale of weak interactions
three ways to look for dark matter particles

- make it
- shake it
- break it
Dark matter in the Universe can annihilate into ordinary matter and change the generic features of cosmic ray energy spectra.

Type I -- Indirect Detection (break it)

- Positrons
- Anti-protons
- Gamma rays
- Neutrinos
- ......
First Result from
the Alpha Magnetic Spectrometer (AMS) Experiment
on the International Space Station.

ISS: 109 m x 80 m
Cost: $100 billion
Life time 20 years

S. Ting
2013
Type II -- Direct Detection (shake it)

We can also wait for dark matter particles hitting the earth.

The deposited energy is typically tens of keV.

We need a quiet place to measure such small energy.
DUSEL Deep Underground Science and Engineering Laboratory at Homestake, SD

Deep Campus

Mid-level

Shallow Lab

Open cut

6 1/2 Empire State Buildings for scale

Engineering

Geoscience

Physics

Astrophysics

Biology

NSF
A Liquid Xenon TPC

- 365 kg/300 kg active
- Dual-phase TPC
- 122 PMTs

Over 200 sensors
- temperatures
- heater powers
- liquid levels
- flow rates
- pmt currents
- grid currents

Patrick Phelps

Monday, April 15, 13
current limits: < 0.1 events/kg/year
Type III -- Collider Searches (make it)

Direct detection probes the dark matter coupling to nucleons

In high energy physics, we build colliders and use proton or anti-proton collision to produce heavy particles
LHC at CERN

Proton-proton
7, 8, 13, 14 TeV  27 km

they discovered the Higgs boson
A dark matter particle produced at the LHC will penetrate the detectors and escape, leaving no trace.
If the collision final state only contains dark matter particles, we don’t know when we should record the events.

From QCD, the quarks inside the proton can radiate additional gluons.

At least, we have one (visible) jet in the final state.
Monojet event

$Pt(jet)=175\text{ GeV}$

$\text{MET}=170\text{ GeV}$
Puzzle 5: Dark Energy

Einstein added a constant in the GR and called it “Cosmological Constant”.

![Pie chart showing the distribution of matter and energy in the universe. Dark Energy constitutes 68.3%, Dark Matter 26.8%, and Ordinary Matter 4.9%.](chart.png)
Puzzle 5: Dark Energy

$\frac{\Lambda}{M_{Pl}^4} = 10^{-120}$

More exotic ideas have been introduced to explain it. Are we living in the multiverse?
Puzzle 5: Dark Energy

In 1987 and before we observed the accelerating universe, Steven Weinberg used the *anthropic principle* to set an upper bound on the CC, which is only one order of magnitude away from the observed one.

If the CC is too large, the stars will not form and hence we can not exist.

Are we satisfied with this line of argument? Can you figure out the explanation for this puzzle?
Thanks