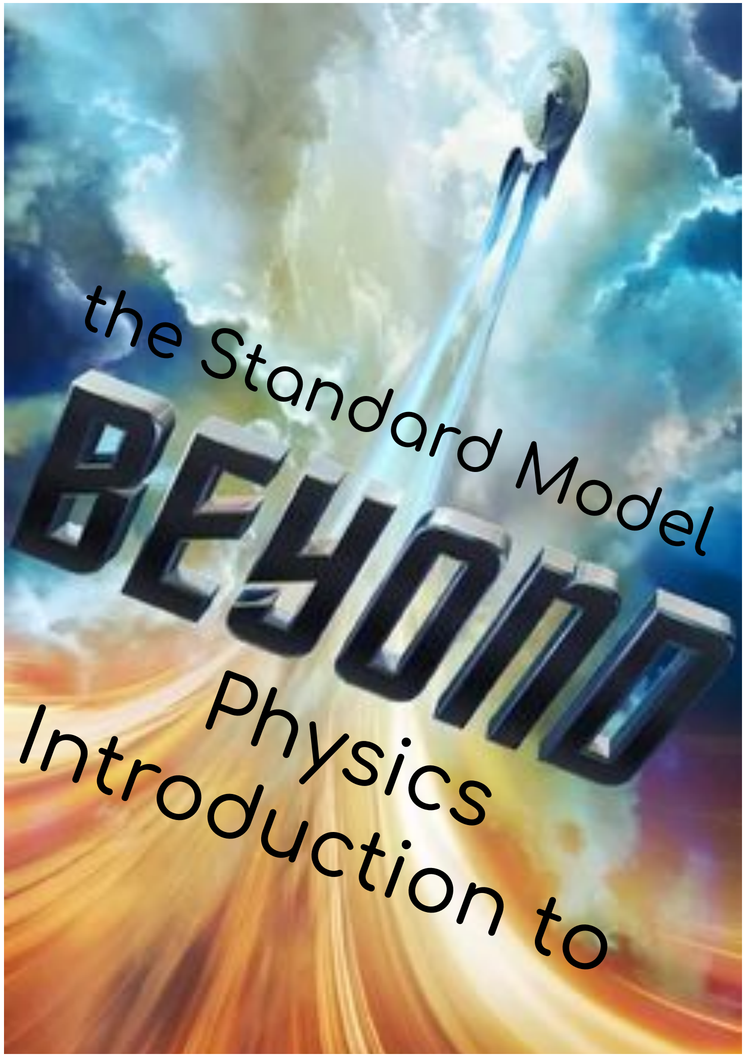
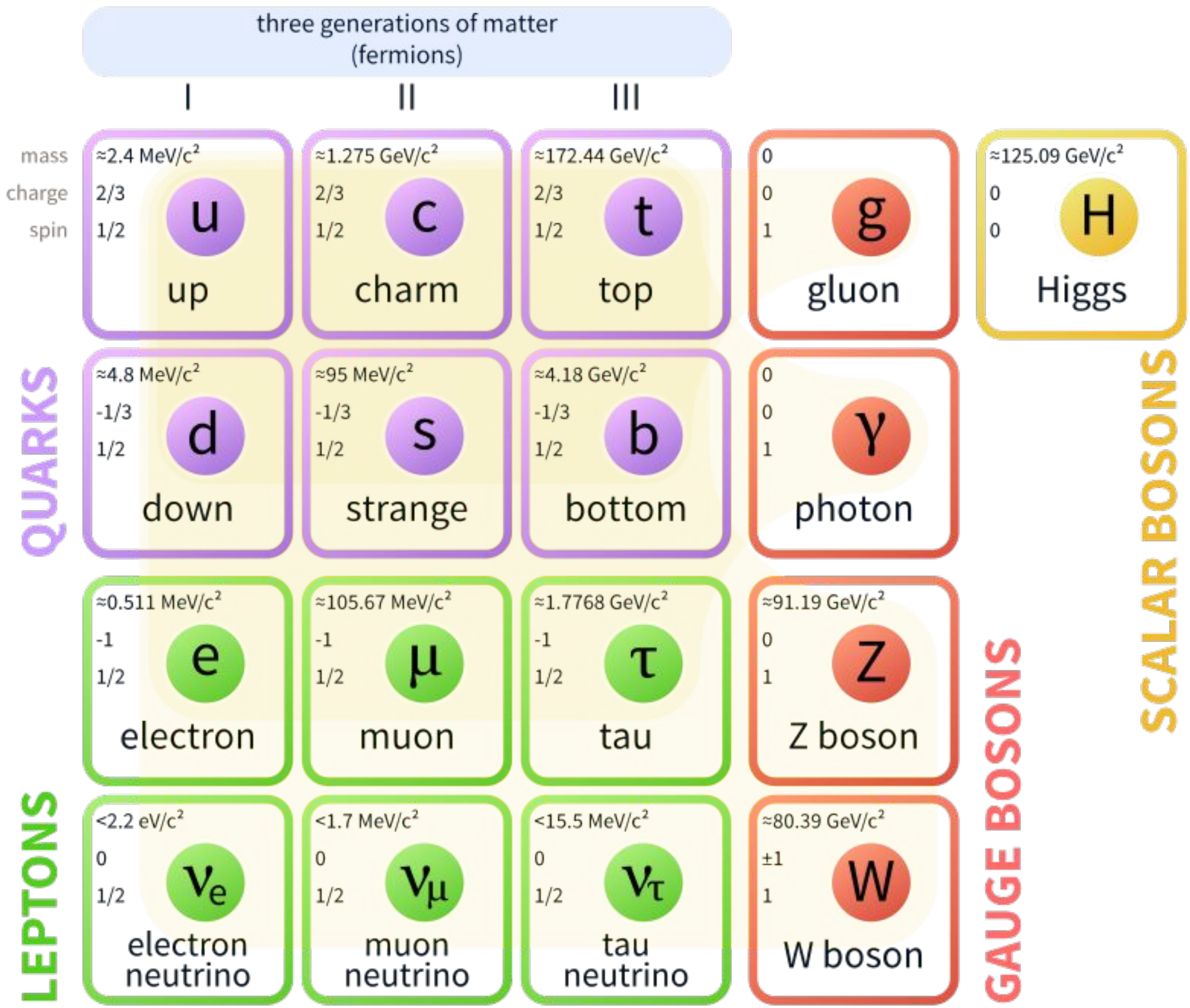


Chakrit Pongkitivanichkul
Khon Kaen University

7 May 2022
MWIT

The Standard Model is a theory of elementary particles and their interactions

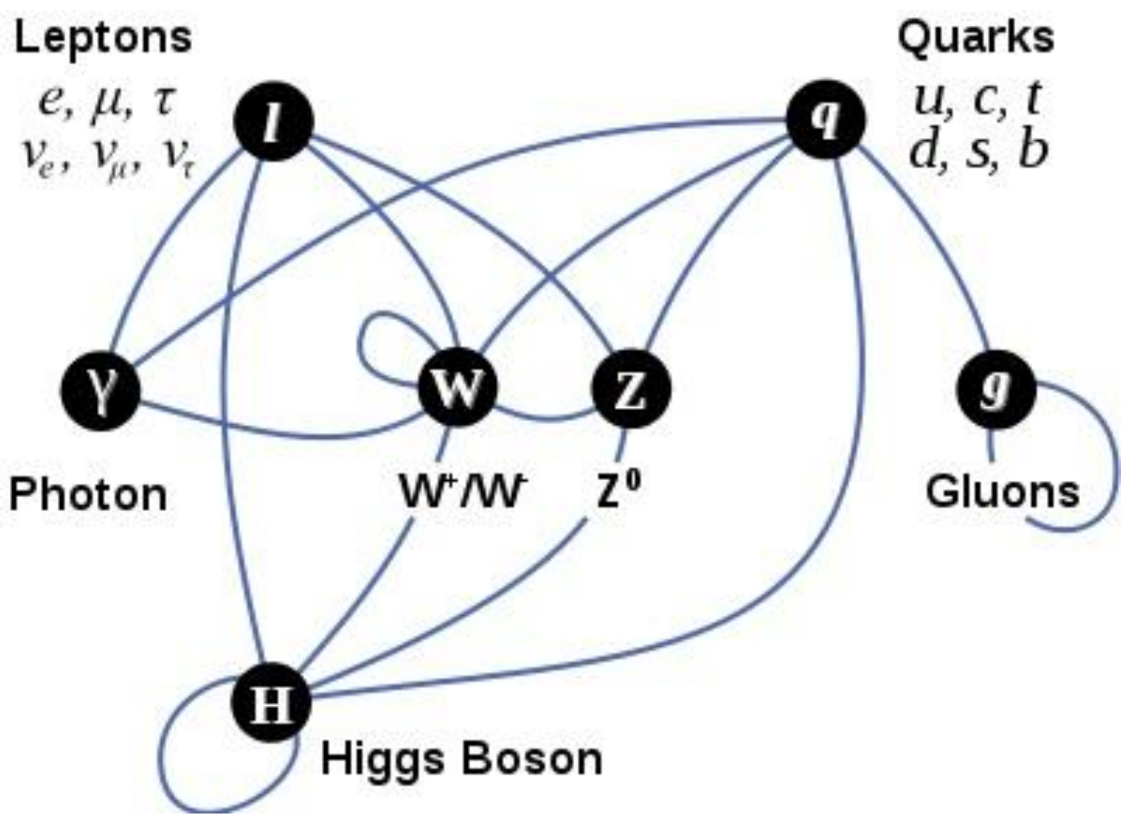
Standard Model of Elementary Particles



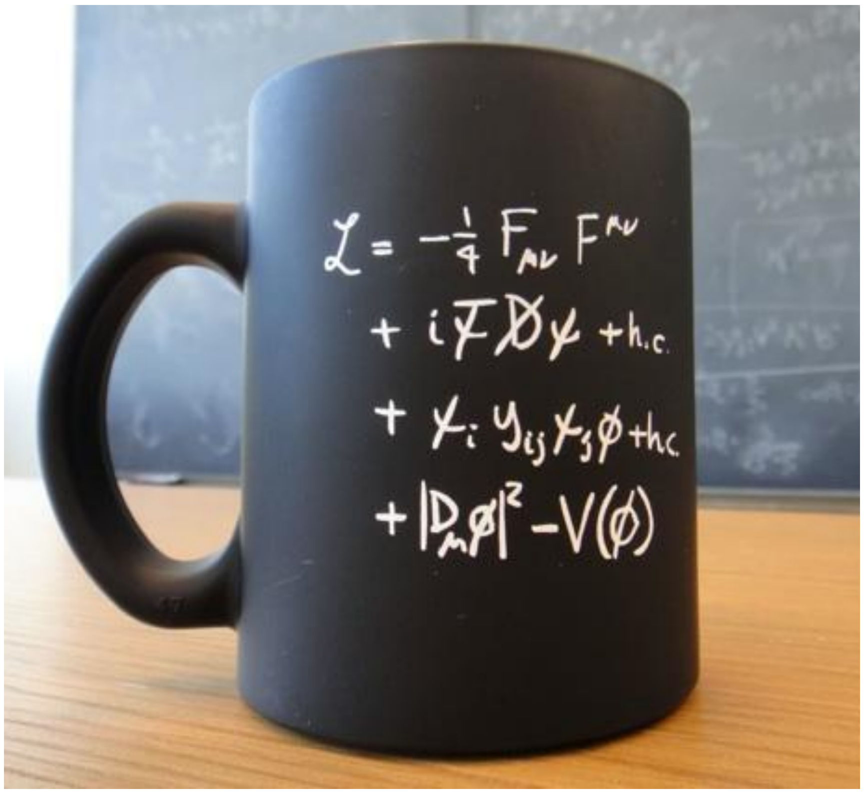
Review on the SM

- There are 3 forces and corresponding mediators
- Electromagnetic
  - Responsible for majority of physics at our scale
  - Mediated by photons
- Weak Nuclear force
  - Nuclear reaction
  - Mediated by W and Z (and Higgs) bosons
- Strong Nuclear force
  - Formation of protons/neutrons
  - Mediated by gluons

Particles and interactions



The *ugly* detail of the SM

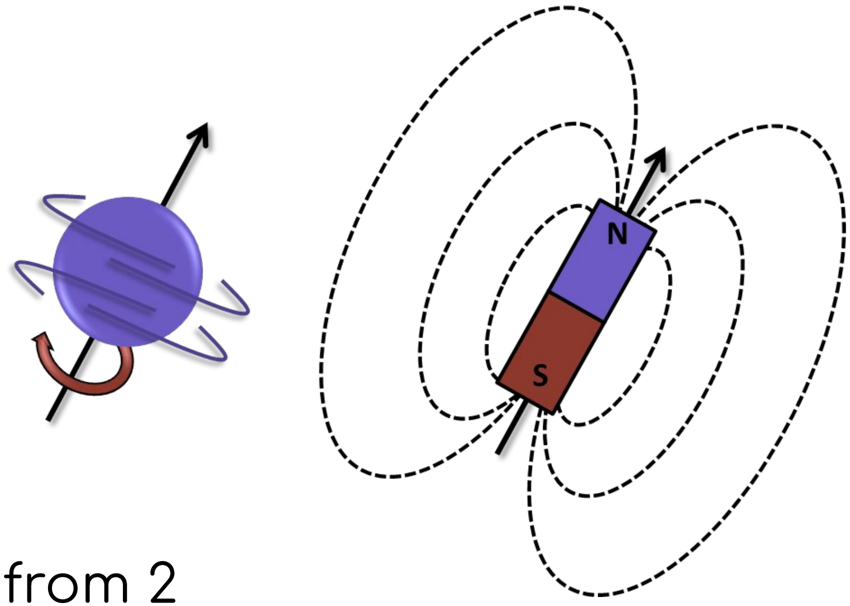


$$
\begin{gathered}
-\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g_s^2 f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \\
\frac{1}{2}ig_s^2(\bar{q}^\sigma_i \gamma^\mu q^\sigma_j)g^a_\mu + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
M^2 W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \frac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H - \\
\frac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2\phi^+\phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \frac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h[\frac{2M^2}{g^2} + \\
\frac{2M}{g}H + \frac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)] + \frac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu \partial_\nu W^-_\mu - \\
W^-_\nu \partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu \partial_\nu W^-_\mu - \\
W^-_\mu \partial_\nu W^+_\mu) + A_\mu(W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - \frac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \\
\frac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + \\
g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] - \\
\frac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2] - \\
gMW^+_\mu W^-_\mu H - \frac{1}{2}g\frac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \frac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - \\
W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \frac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \\
\phi^+\partial_\mu H)] + \frac{1}{2}g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\frac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + \\
igs_w MA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\frac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + \\
igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \frac{1}{4}g^2 W^+_\mu W^-_\mu[H^2 + (\phi^0)^2 + 2\phi^+\phi^-] - \\
\frac{1}{4}g^2\frac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2\phi^+\phi^-] - \frac{1}{2}g^2\frac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + \\
W^-_\mu\phi^+) - \frac{1}{2}ig^2\frac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + \\
W^-_\mu\phi^+) + \frac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\frac{s_w}{c_w}(2c_w^2 - 1)Z^0_\mu A_\mu\phi^+\phi^- - \\
g^1 s_w^2 A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial + m_e^\lambda)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m_u^\lambda)u^\lambda_j - \\
\bar{d}^\lambda_j(\gamma\partial + m_d^\lambda)d^\lambda_j + igs_w A_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \frac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)] + \\
\frac{ig}{4c_w}Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\frac{4}{3}s_w^2 - \\
1 - \gamma^5)u^\lambda_j) + (\bar{d}^\lambda_j\gamma^\mu(1 - \frac{8}{3}s_w^2 - \gamma^5)d^\lambda_j)] + \frac{ig}{2\sqrt{2}}W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) + \\
(\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \frac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1 + \\
\gamma^5)u^\lambda_j)] + \frac{ig}{2\sqrt{2}}\frac{m_e^\lambda}{M}[-\phi^+(\bar{\nu}^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] - \\
\frac{g}{2}\frac{m_e^\lambda}{M}[H(\bar{e}^\lambda e^\lambda) + i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}}\phi^+[-m_d^\kappa(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + \\
m_u^\lambda(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j] + \frac{ig}{2M\sqrt{2}}\phi^-[m_d^\lambda(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m_u^\kappa(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1 - \\
\gamma^5)u^\kappa_j] - \frac{g}{2}\frac{m_u^\lambda}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \frac{g}{2}\frac{m_d^\lambda}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \frac{ig}{2}\frac{m_u^\lambda}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \\
\frac{ig}{2}\frac{m_d^\lambda}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \\
\frac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- - \partial_\mu\bar{X}^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- - \\
\partial_\mu\bar{X}^+ Y) + igc_w W^-_\mu(\partial_\mu\bar{X}^- X^0 - \partial_\mu\bar{X}^0 X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^- Y - \\
\partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+ X^+ - \partial_\mu\bar{X}^- X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+ X^+ -
\end{gathered}
$$

The theory is
only as good as its predictions

How good is the SM?

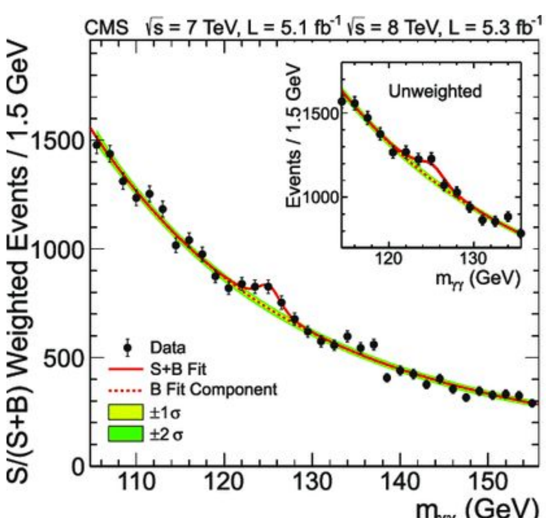
The Electron Magnetic Dipole Moment

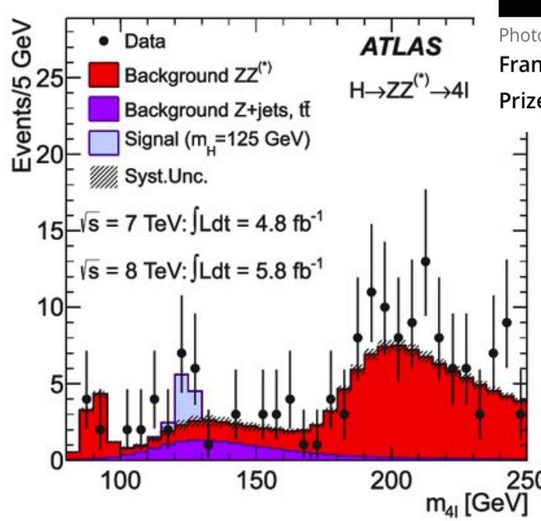


- The relation between angular momentum and magnet property
- Dirac equation predicts g = 2
- Quantum effects make it differs from 2
- This is predicted by the SM which agrees with experiments (g-2)
  - Theory: 1.00115965217760(520)
  - Experiment: 1.00115965218073(28)
- The most accurate prediction ever made by scientific theories

Higgs boson discovery

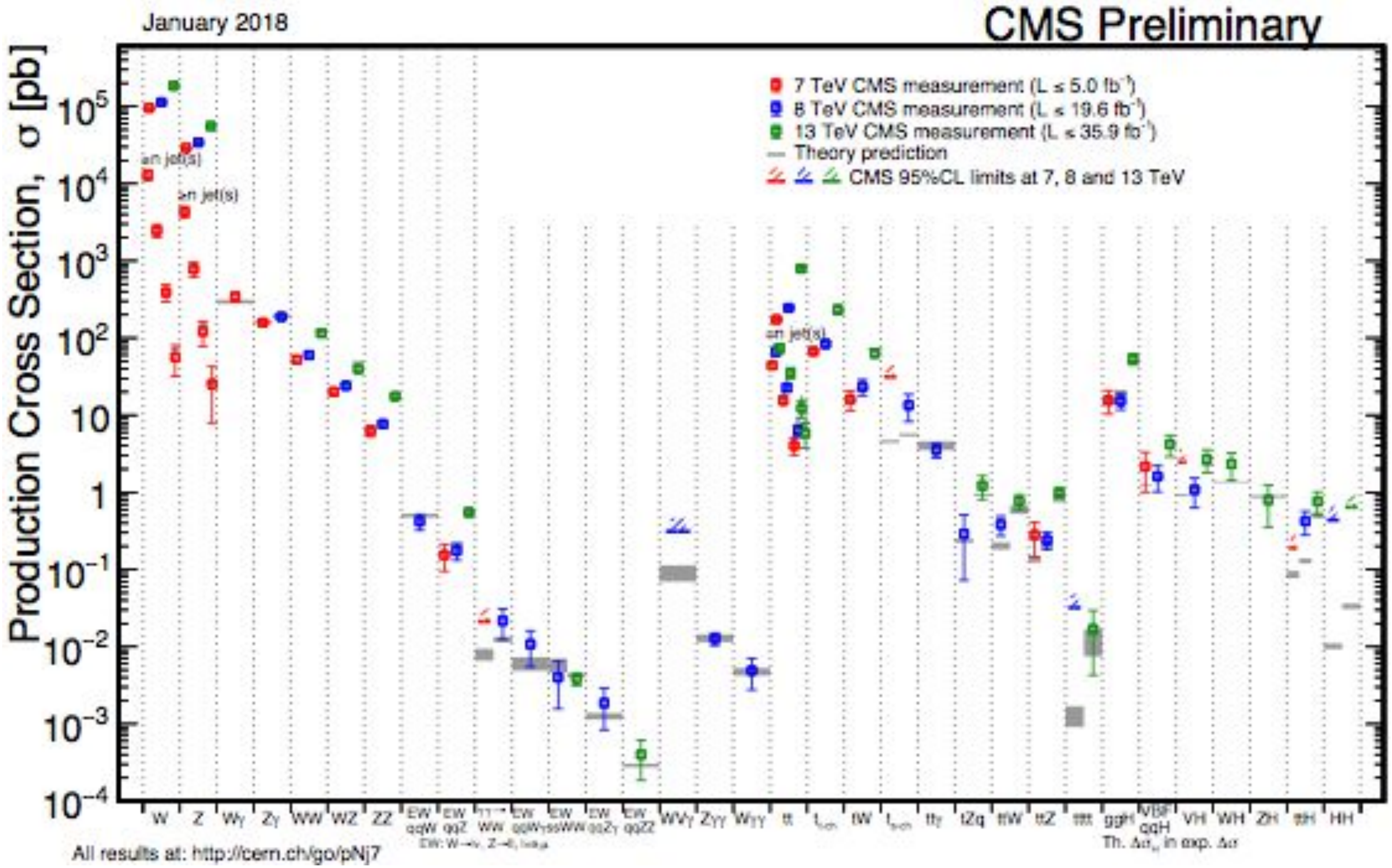
The SM predicts the existence of a spin 0 particle, the Higgs boson

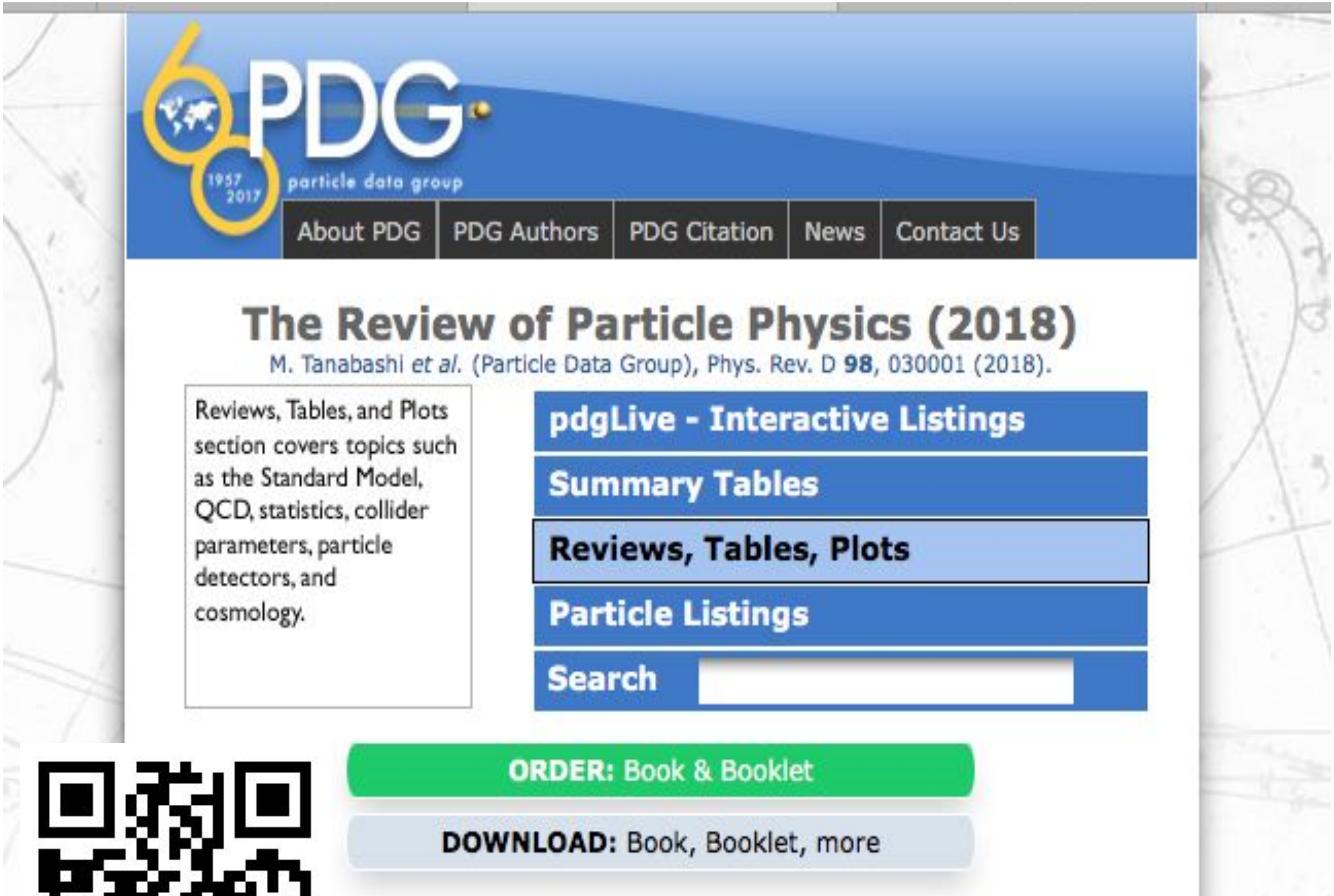




Discovered at the LHC in 2012

It has been **remarkably consistent** with the SM



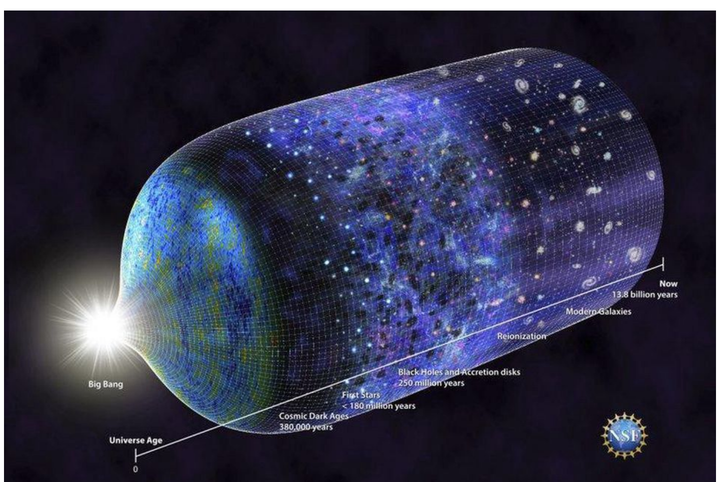


http://pdg.lbl.gov

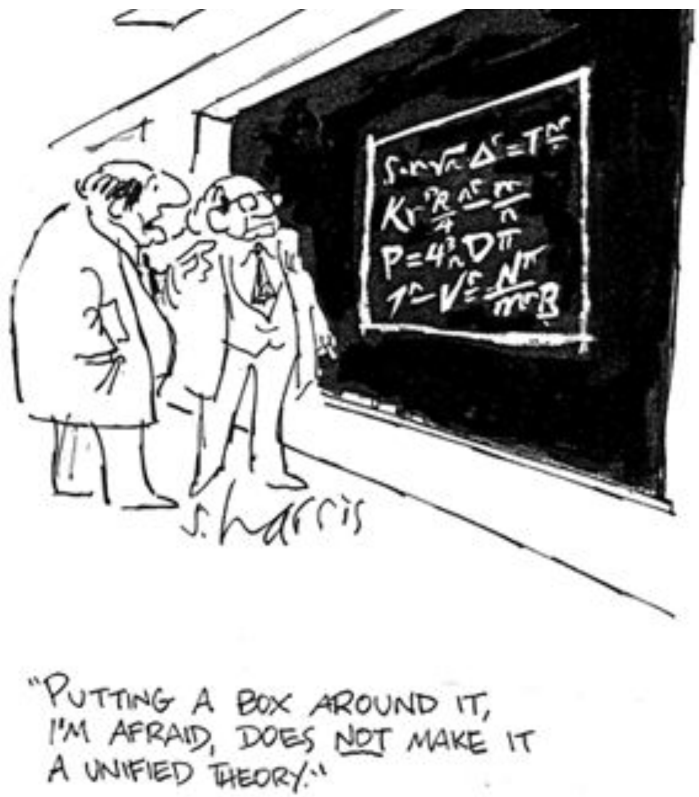
If the SM is successful then why do we care about a theory beyond the SM?

Nature hints

- Experimental
    - Neutrino masses
    - Dark matter
    - Matter-antimatter asymmetry
    - Potential signals



- Theoretical
    - Higgs mass
    - Unification of forces



Neutrino masses

Homestake Experiment

- Nuclear fusion in the sun also produces neutrinos as a byproduct.
  - Only electron neutrinos (ν_e) are produced
  - Knowing the amount of energy from the sun

    $\Rightarrow$ amount of ν_e.
- First detected by the Homestake experiment in 1970.
- neutrino capturing process

$$\nu_e +^{37}\mathrm{Cl} \rightarrow^{37}\mathrm{Ar}^+ + e^-$$

Solar Neutrino Problem

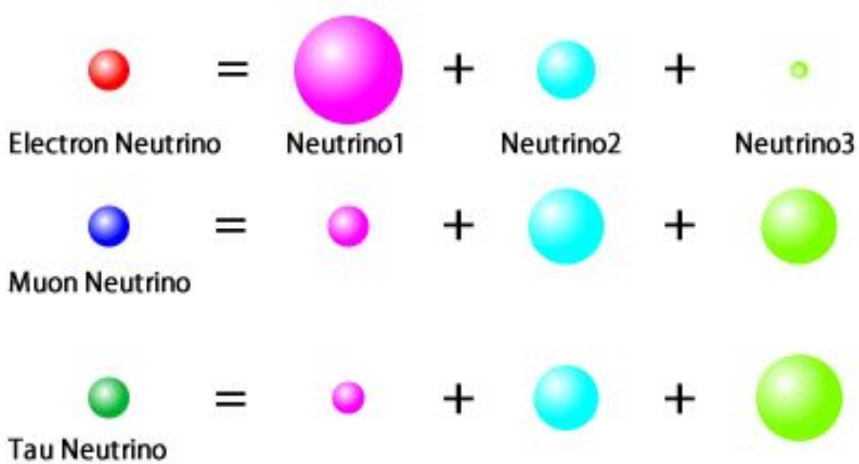
- Detect only ~⅓ of the expected ν_e.
- Where is the missing ⅔??
- The detector was sensitive to ν_e only, but not ν_μ and ν_τ
- Solar neutrinos change from $\nu_e \Longrightarrow \nu_\mu$ and ν_τ on their way to Earth
- This is called *"Neutrino Oscillation"*
- Neutrino Oscillation was later confirmed by SNO and Super-K (Nobel Prize 2015)

Why do neutrino oscillate?

- Neutrino is produced by weak interaction
- Produced as ν_e, ν_μ, ν_τ
- Its evolution is governed by the Hamiltonian
- If flavoured neutrino ≠ mass eigenstates, the evolution for its components is different => flavour changing effect
- Neutrino oscillation = massive neutrinos

Neutrino Oscillation

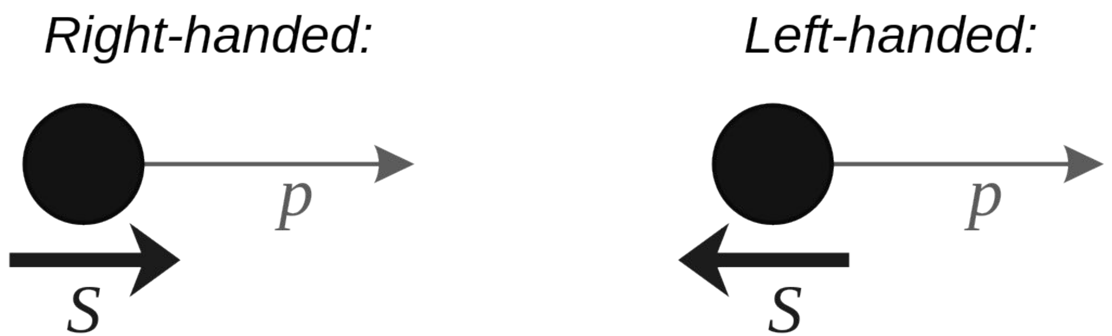
$$
\begin{aligned}
|\psi_e(t)\rangle &= e^{i\hat{H}t}\left(c_1|\psi_1\rangle + c_2|\psi_2\rangle + c_3|\psi_3\rangle\right) \\
&= c_1|\psi_1\rangle e^{iE_1 t} + c_2|\psi_2\rangle e^{iE_2 t} + c_3|\psi_3\rangle e^{iE_3 t}
\end{aligned}
$$



Time evolution changes the flavours if the basis states have different masses

The Importance of Mass

Neutrino has spin ½. There are two intrinsic possible spin orientations if neutrino were massless



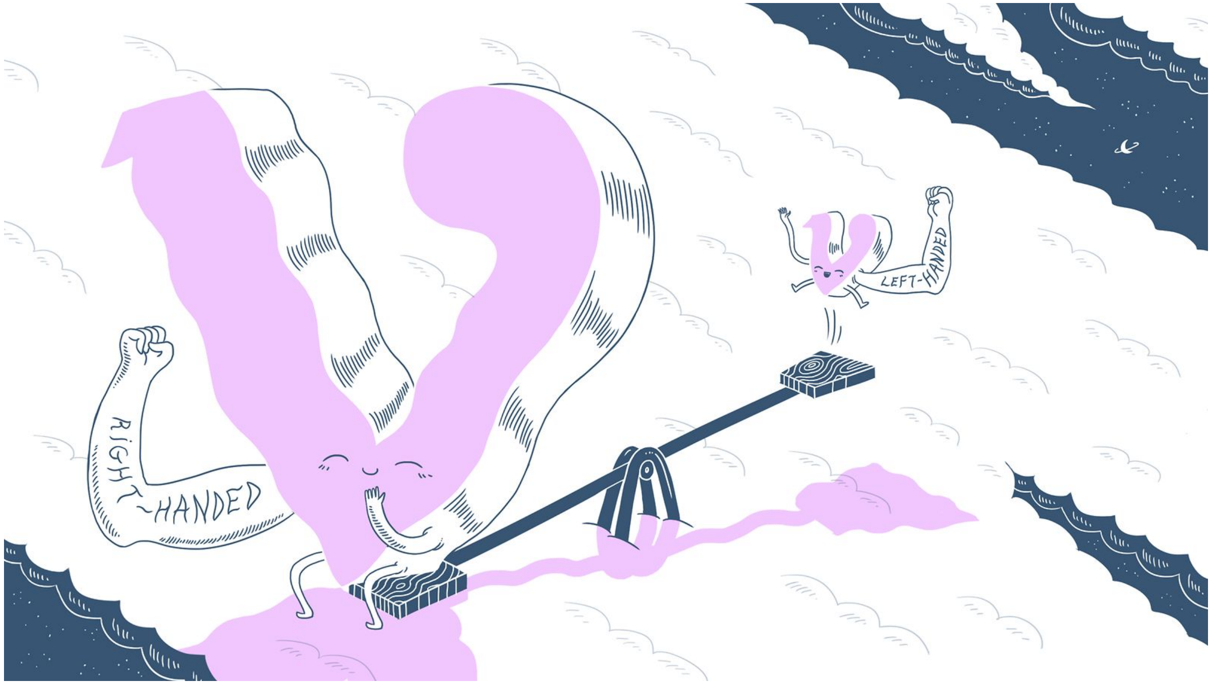
Massive neutrino: We can change the reference frame such that left ↔ right

Massive neutrino requires both left and right handed

The Importance of Mass

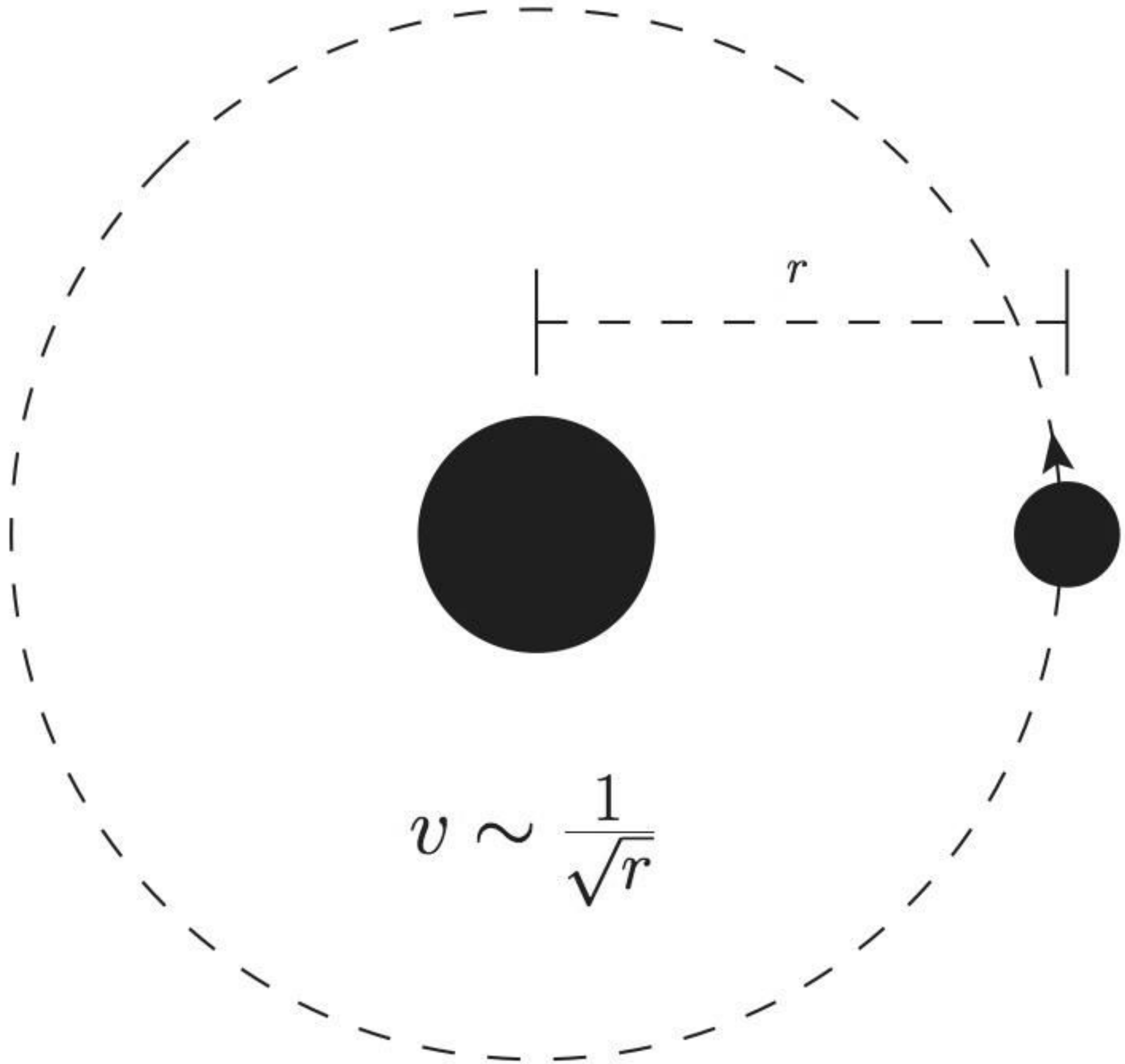
However, the SM only allows for left-handed neutrinos

An existence of right-handed neutrino implies a theory beyond the SM physics!!

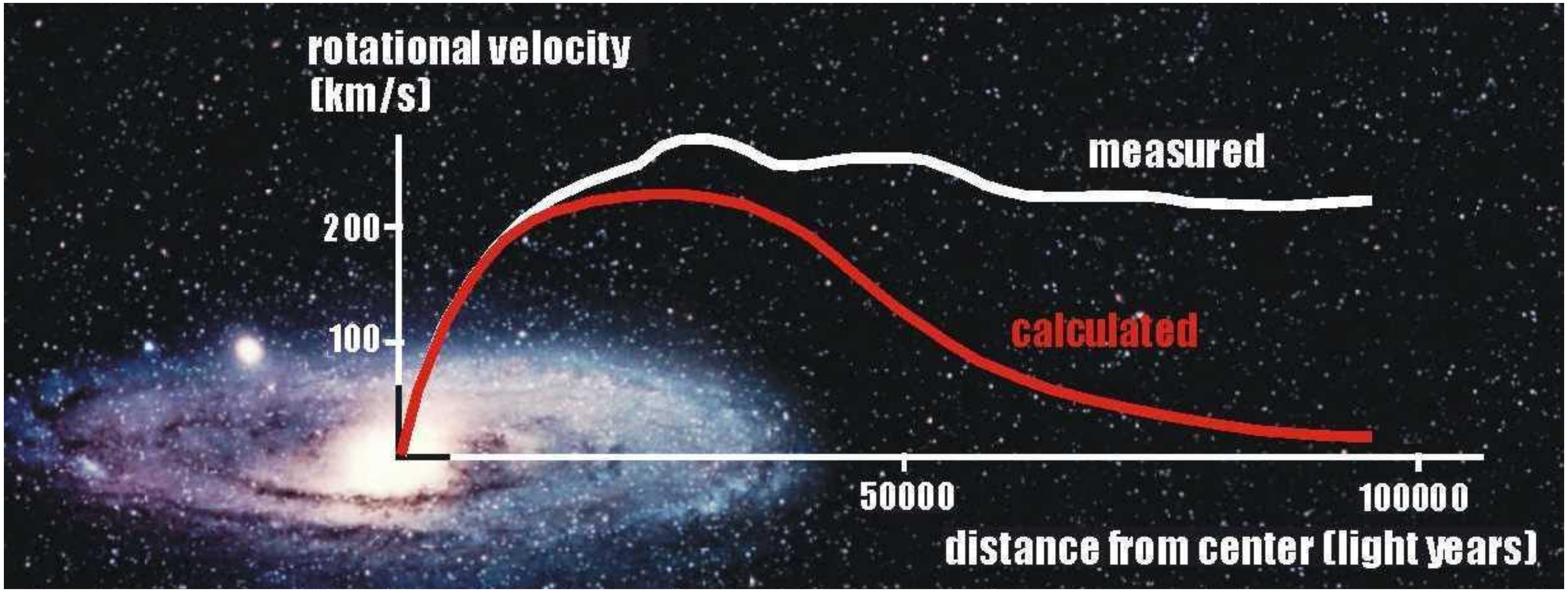


Dark Matter

Warm up Exercise

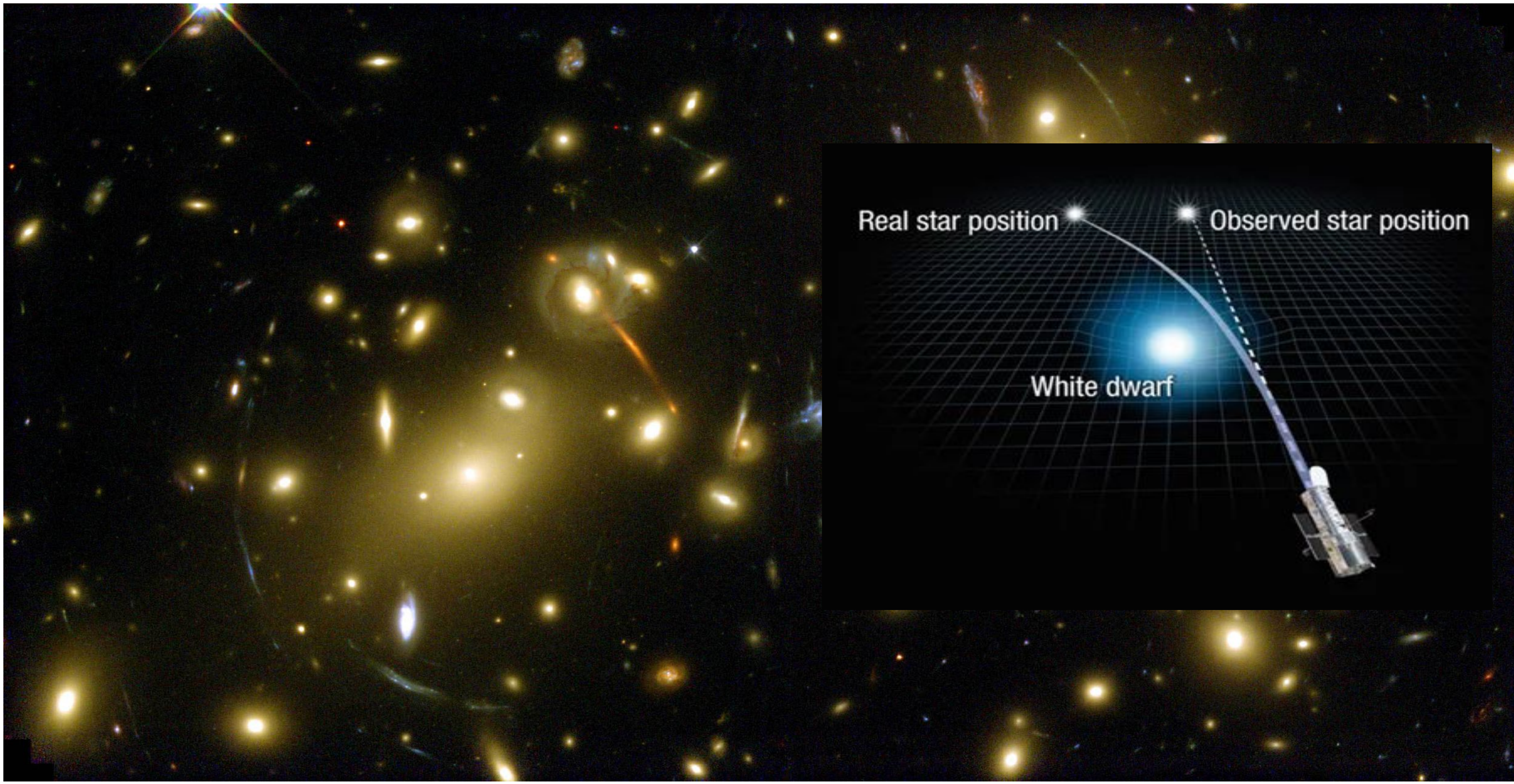


Dark matter



- Need more masses to support high orbital velocities
  - These masses do not emit photon
  - “Dark matter” (DM)
- Masses must extend beyond the stars region => DM halo
- We see this effect in other galaxies

Gravitational Lensing



The Bullet Cluster

Red = gas heating up from collision (X-ray)

Blue = Majority of mass (Gravitational lensing)

DM don't like to interact!!

Structure Formation

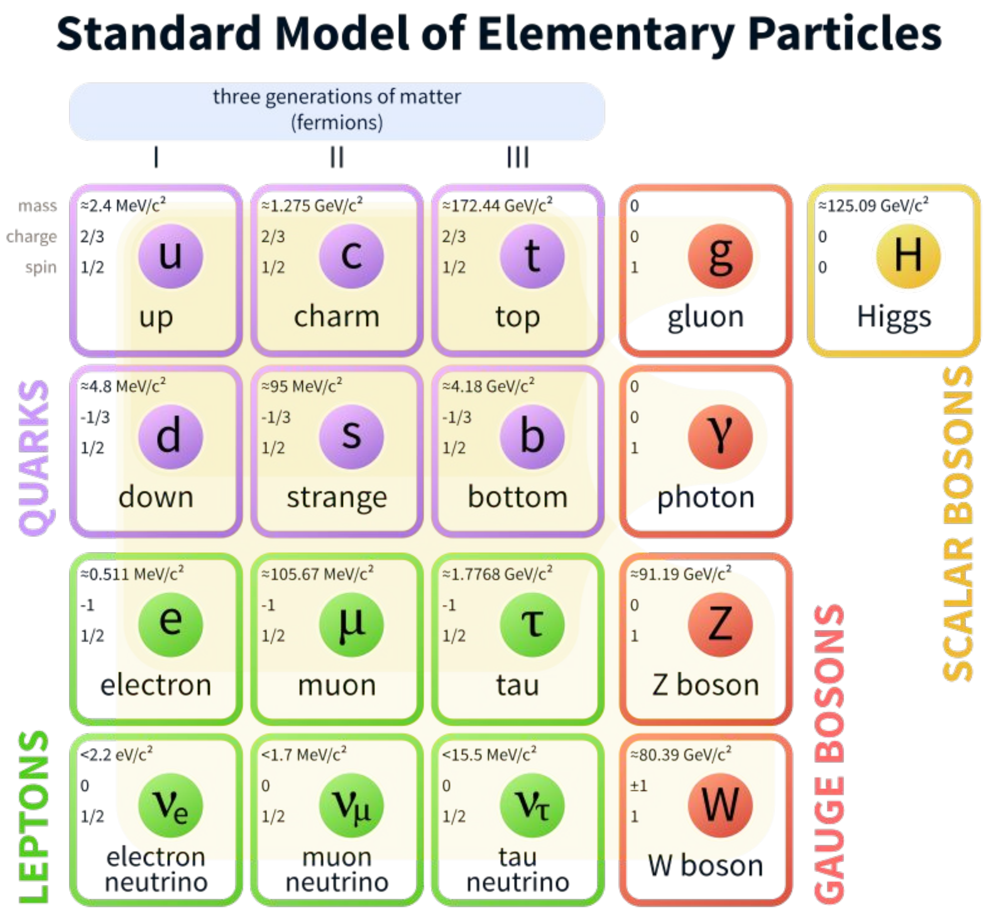
Dark Matter

Visible Matter

Things we know about Dark Matter

- DM is massive
- DM is long-lived (at least 14 billions years)
- DM does not emit/reflect light
- DM is weakly interacting

Things we don't know about Dark Matter



- <u>Its identity</u>
- DM does not fit in the SM
- DM identity requires a theory beyond standard model

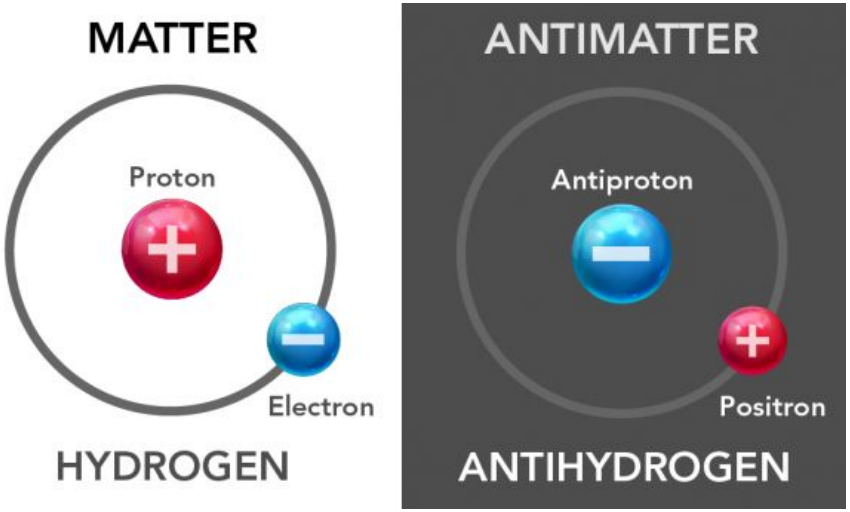
Matter/Anti-matter asymmetry

Matter Dominated Universe

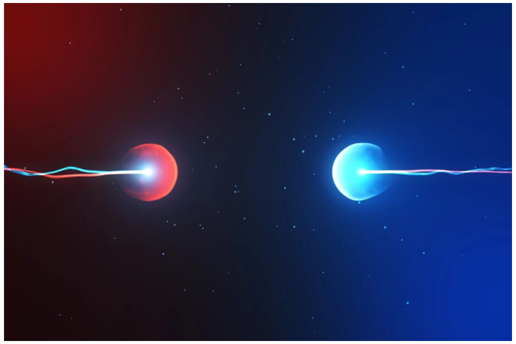
We are surrounded by matters: protons, neutrons and electrons

Where are the anti-matters?

How do we know that there are not too many anti-matters in the universe?

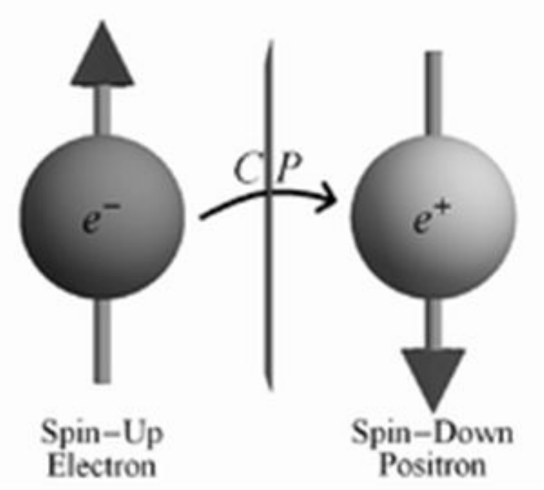


Annihilation



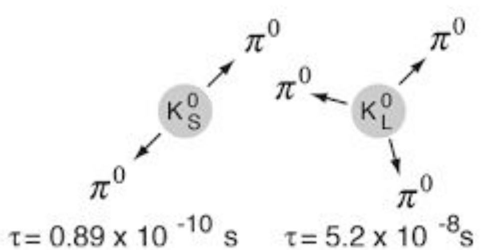
CP symmetry = Matter/Anti-matter symmetry

- Charge conjugation (C) = changing the sign of quantum number
- Parity transformation (P) = mirror reflection (changing left-right)
- Matter and antimatter such as electron and positron <u>are related by CP symmetry</u>



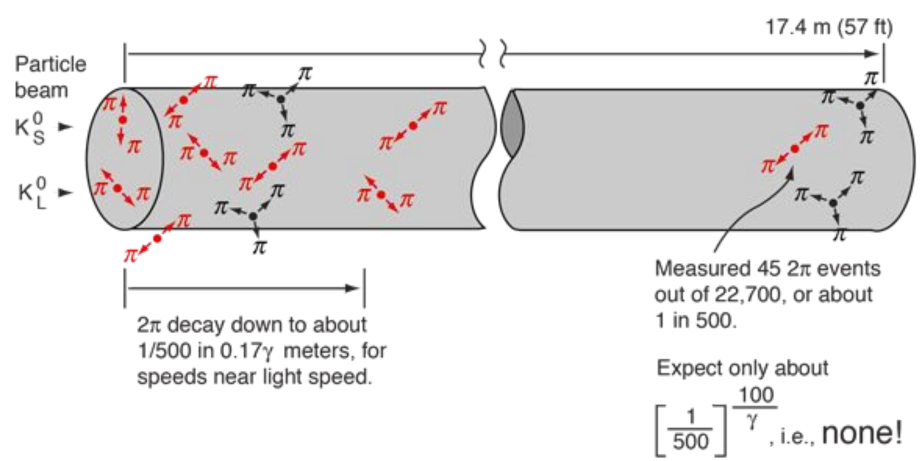
We need CP symmetry to be broken

- In the SM, CP symmetry is violated in the quark sector
- Cabibbo-Kobayashi-Maskawa (CKM) matrix (Nobel Prize for K and M in 2008)
- CP violation from CKM matrix <u>has been verified by many experiments</u> (BaBar, Belle, Fermilab and CERN)



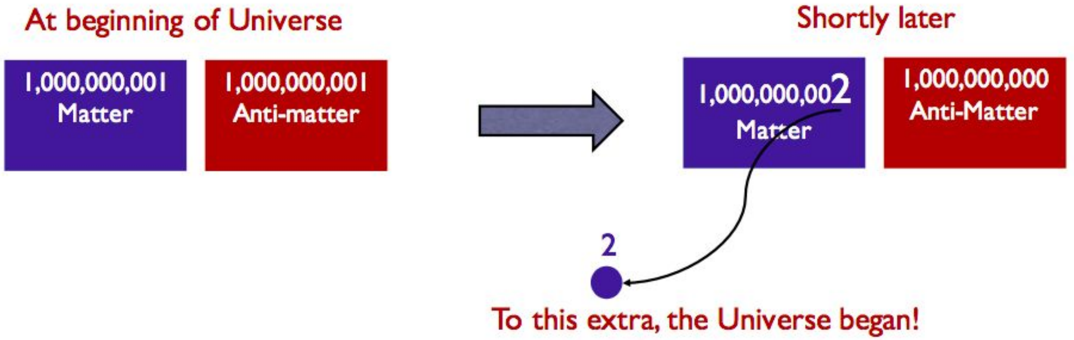
$$K^0_S = \frac{K^0 - \bar{K}^0}{\sqrt{2}}$$

$$K^0_L = \frac{K^0 + \bar{K}^0}{\sqrt{2}}$$



It's not enough!!

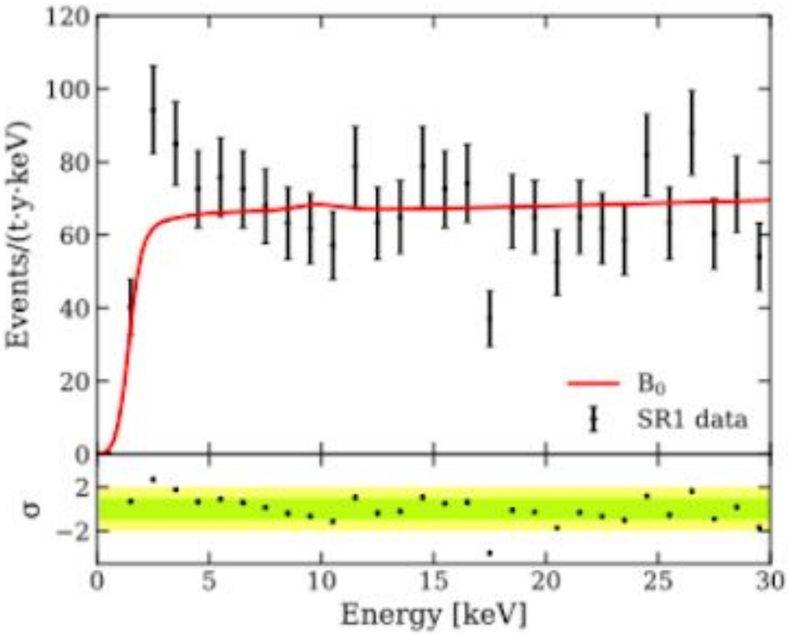
- Detailed calculation shows CP violation from CKM matrix is not enough to generated the observed matter/anti-matter asymmetry (Sakharov's conditions)
- A new source for the CP violation is needed => Beyond Standard Model



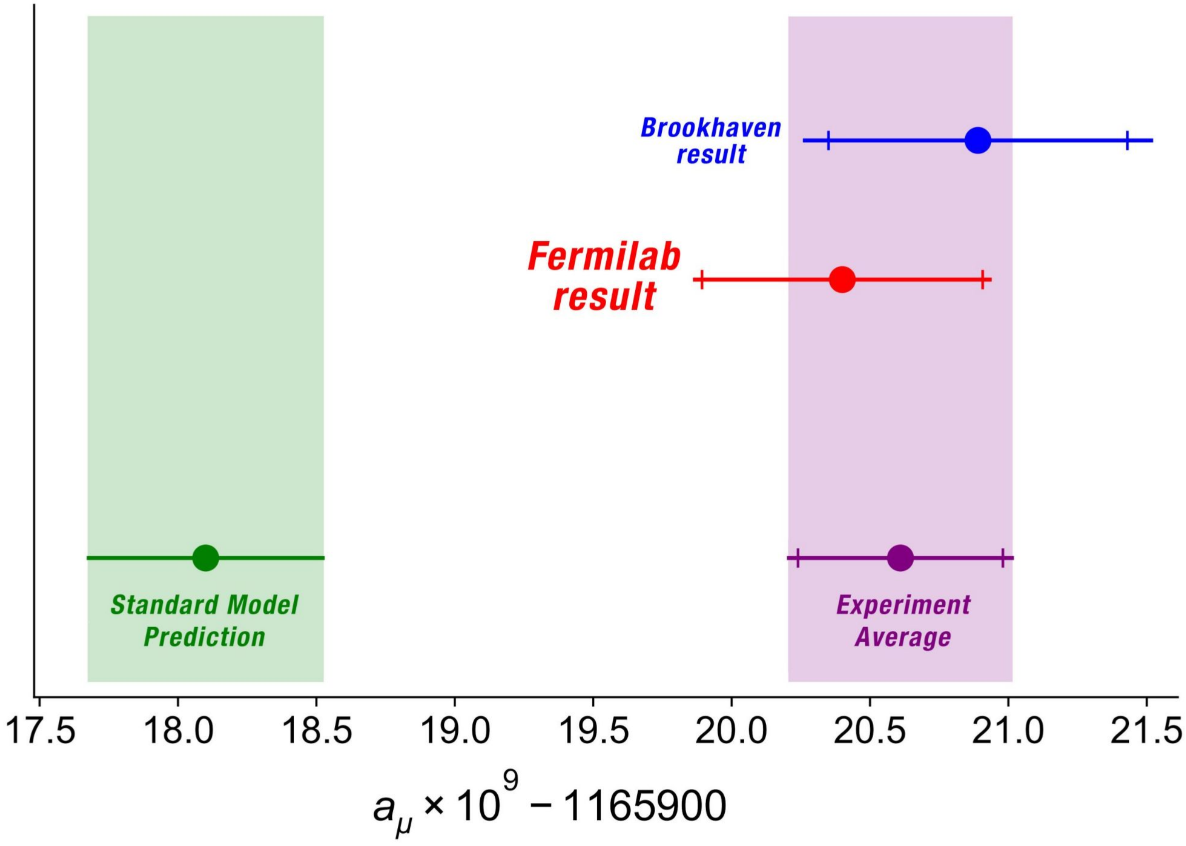
Baryon asymmetry: $\frac{n_B - n_{\overline{B}}}{n_\gamma} \approx 6 \times 10^{-10}$

Potential signals

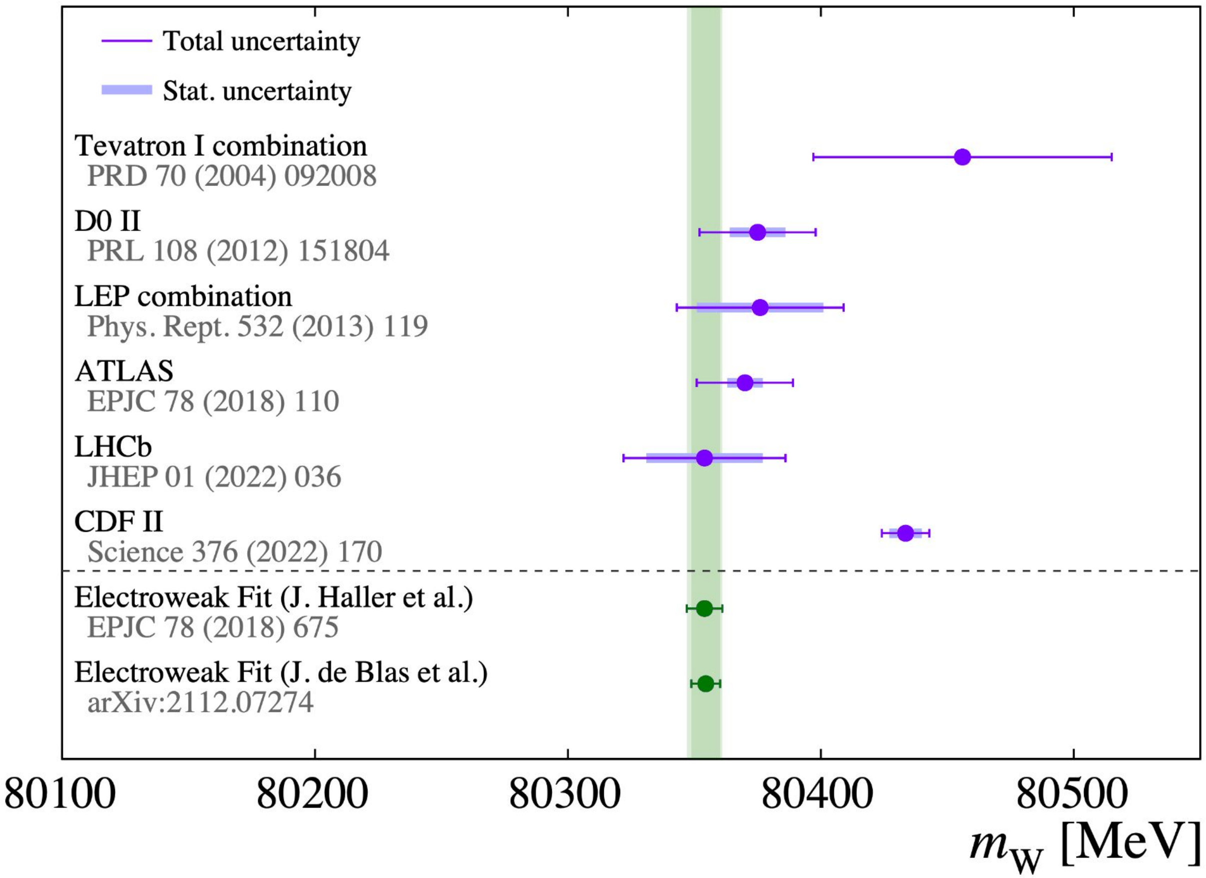
XENON1T electron recoil experiments



Muon anomalous magnetic dipole moment (g-2)



W mass measurement

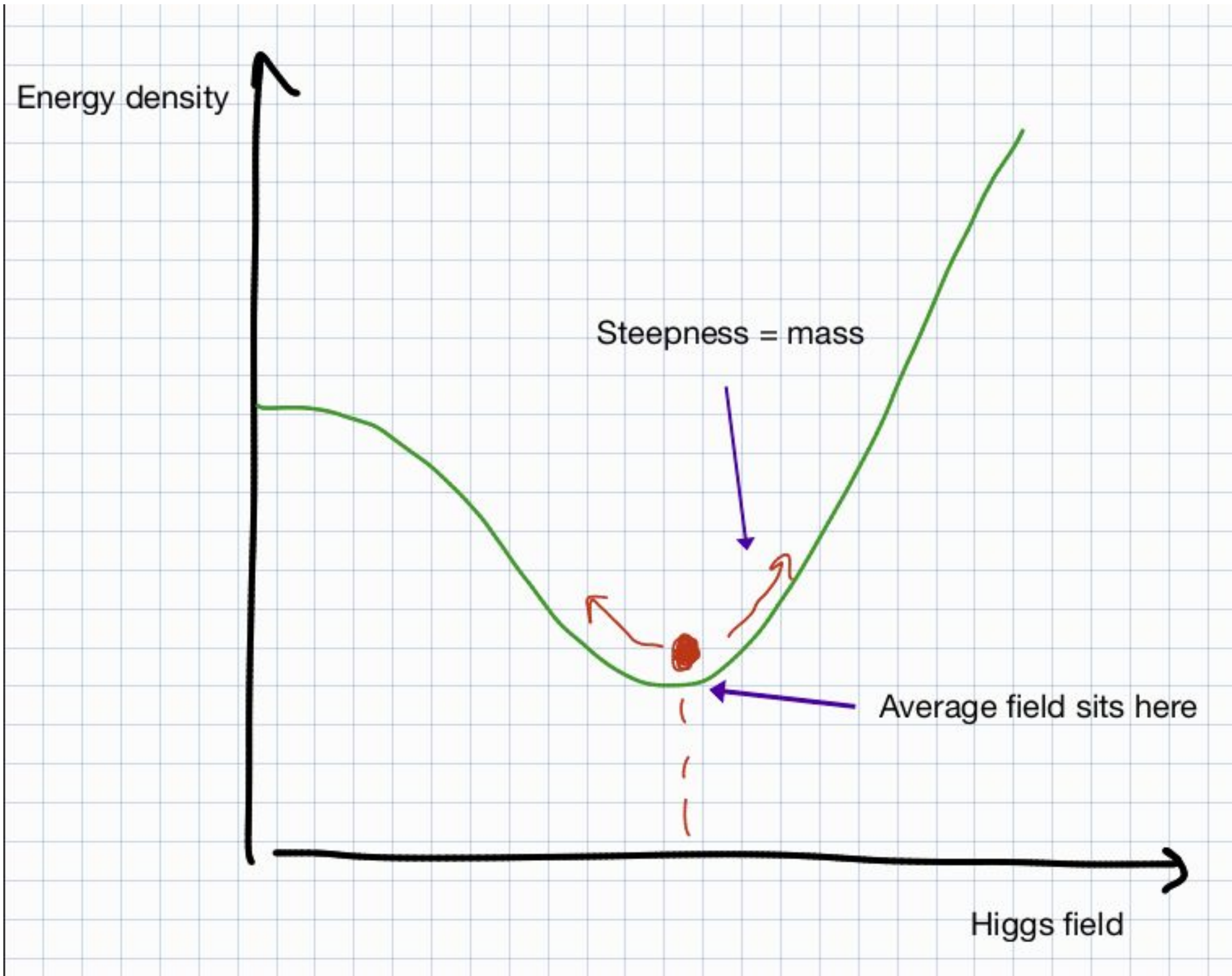


Theoretical Hints

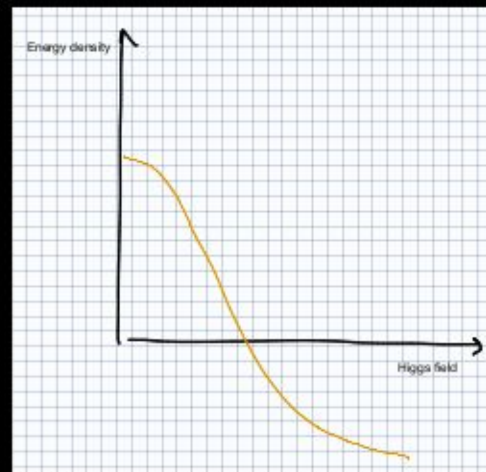
Higgs mass puzzle

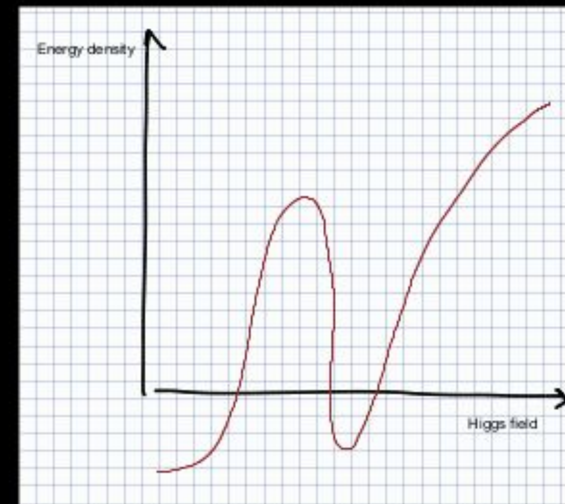
- Higgs mass is found to be around Electroweak scale (125 GeV)
- Theoretically Higgs mass should have been much higher
- Higgs is fundamental spin-0 scalar particle = no protection (symmetry) from quantum correction
- Need a careful balance between quantum corrections

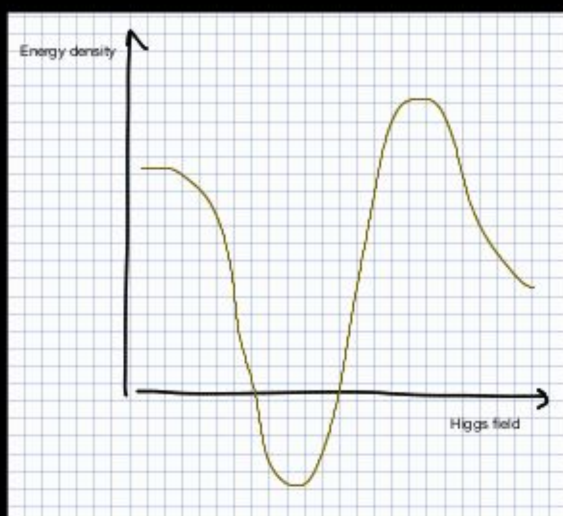
How a field gets mass?



Quantum Mess





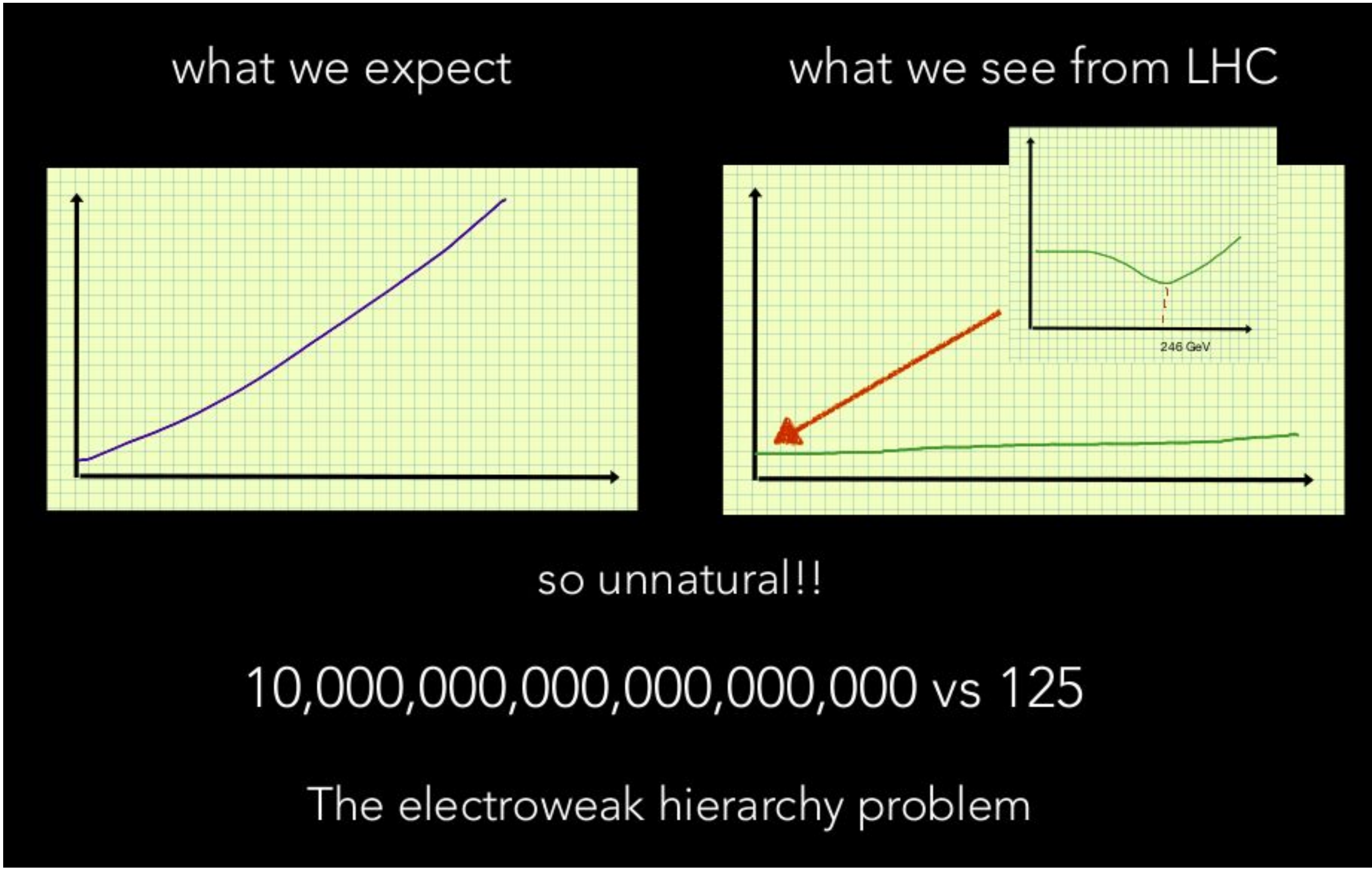


. . . .

(where each potential is drawn up to the maximum where the calculation is unreliable)

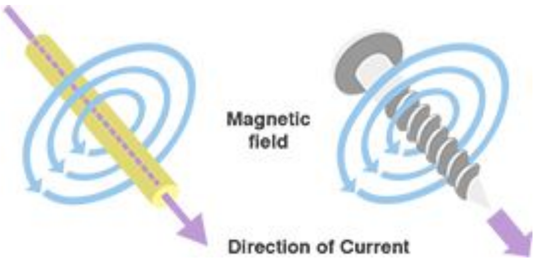
≈10,000,000,000,000,000,000 GeV

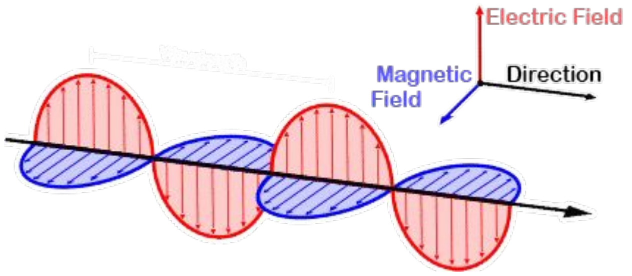
Unnatural = Fine Tuning



Unification Dream

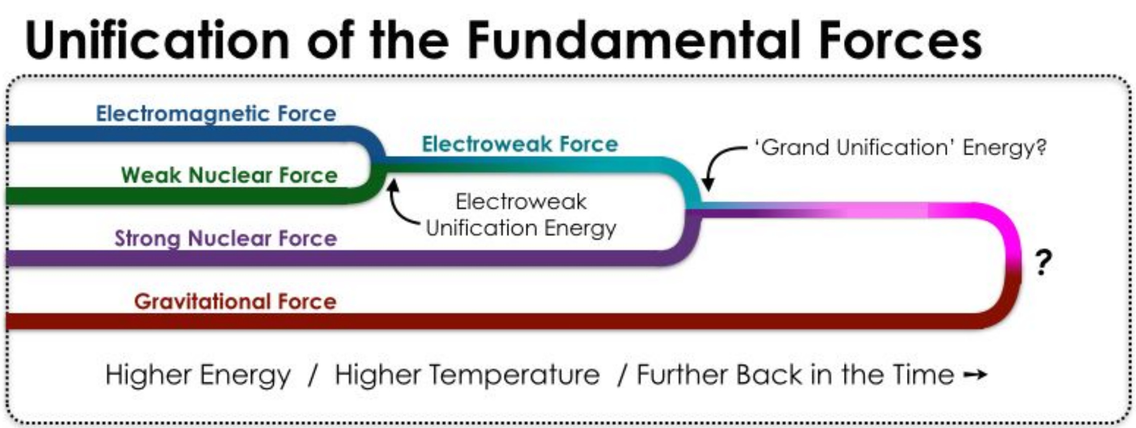
- Frictions, chemical reaction, etc. are facets of electric force
- Maxwell equations → Electric and magnetic forces are just <u>two sides of the electromagnetic force</u>
- In physics, the better we understand, the less forces we tend to have





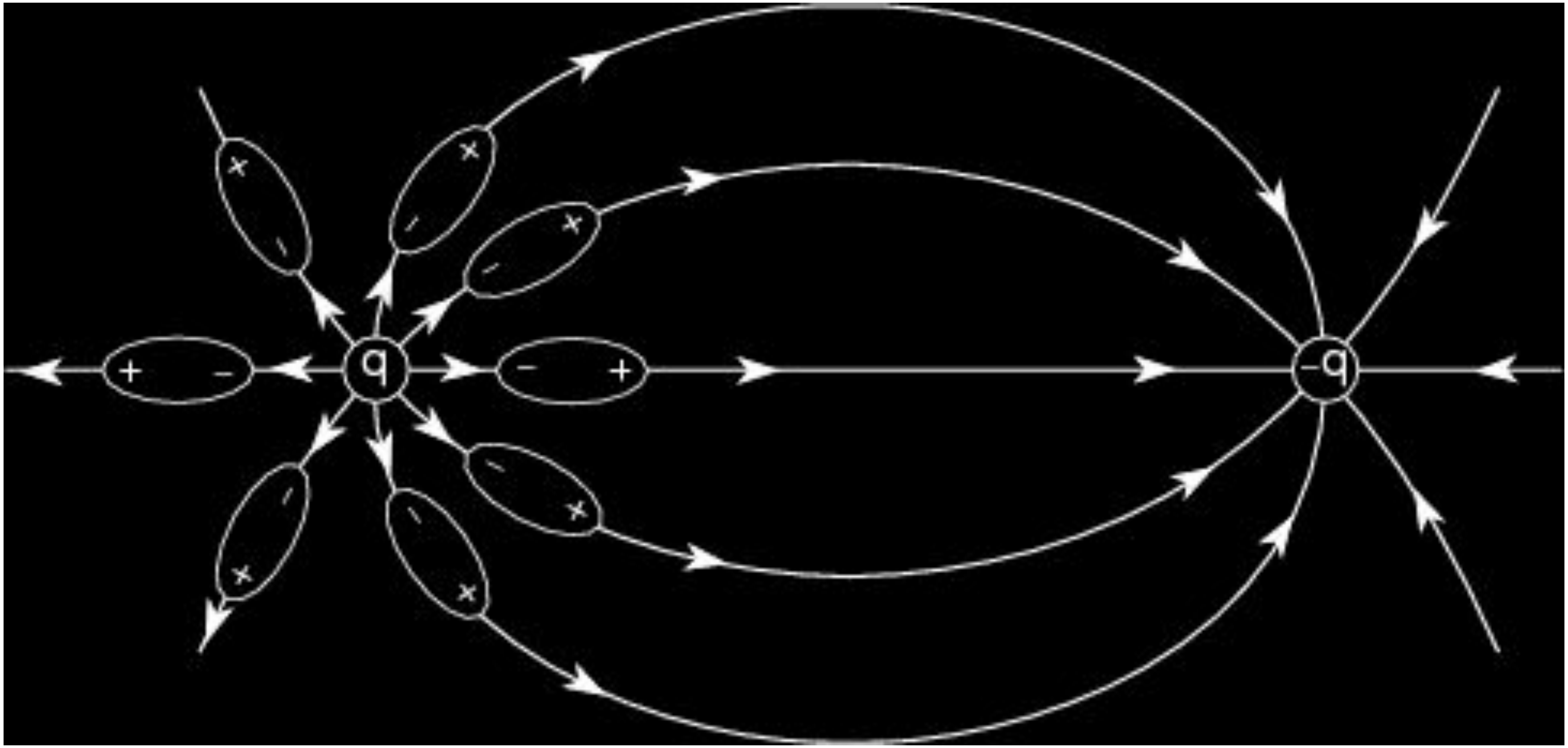
A Grand Unified Theory (GUT)

- The combination of weak and electromagnetic force = electroweak theory which is a part of the Standard Model
- The electroweak and strong force seem to be able to combine
- Gravity is too difficult, so we will just ignore it
- However, the strength of the forces are vastly different



Space is not empty!!

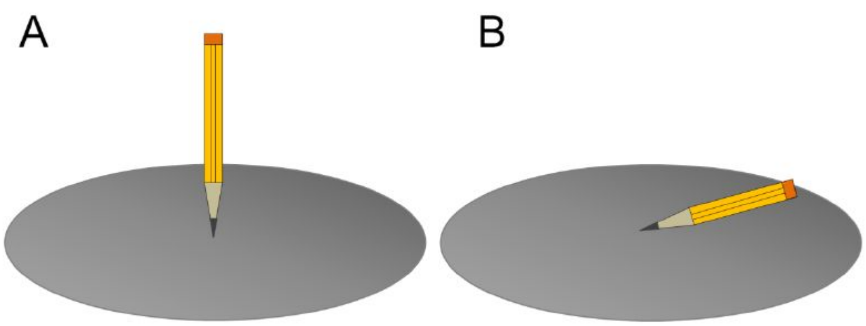
Physical parameters (masses, charges) can be varied depending on the energy scale of the experiment



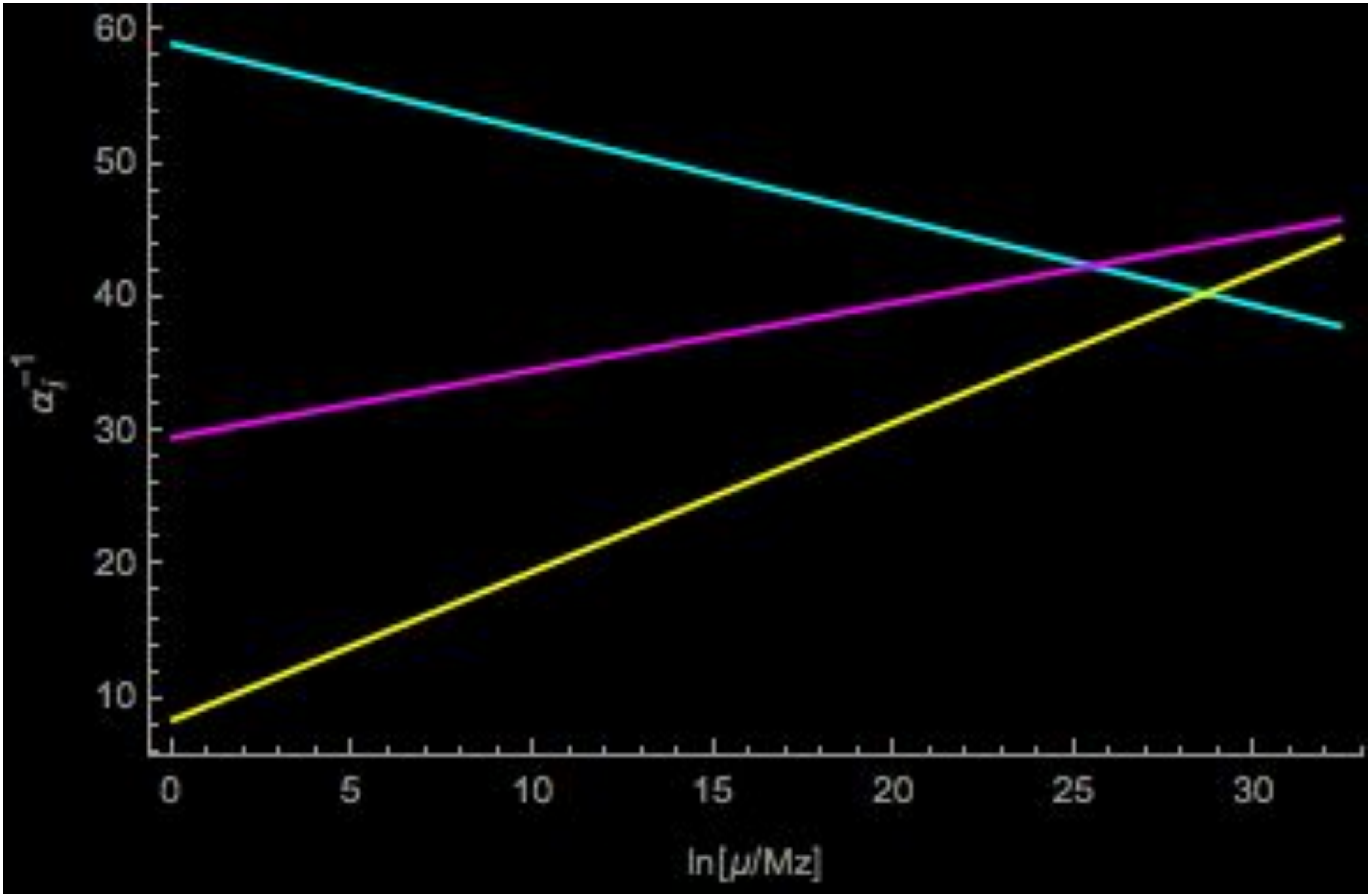
Symmetry Breaking

If the unified force exists, how do we realise three different forces at lower scale?

The answer is similar to the story of Higgs and the Electroweak theory = spontaneous breaking



Standard Model does not deliver?



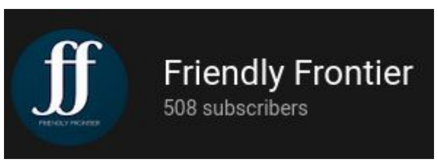
Conclusion

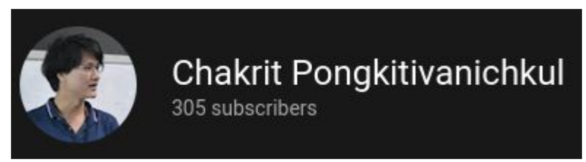
- The Standard Model is <u>the most successful theory human ever invented</u>
- But *it is not a complete theory*
    - Neutrino masses, dark matter, matter/anti-matter asymmetry, …
    - Higgs mass, unification of forces, …
- Experiments at higher energies/higher precision are needed to complete our understanding
- Nature is full of mysteries waiting to be understood → the breakthrough might be around the corner

Thank you

If you want to learn more...

- 4^{th} Thailand School on High-Energy and Astro-Physics (SHEAP 2022): Gravitational Wave (NARIT ~July)
- โครงการอบรมฟิสิกส์อนุภาคพื้นฐาน 2565 (ส่วนภูมิภาค) ณ. มหาวิทยาลัยขอนแก่น (~สิงหาคม)





Quiz time

- ข้อใดต่อไปนี้กล่าวถูกต้องเกี่ยวกับทฤษฎีทางฟิสิกส์
  - ทฤษฎีที่ดีคือทฤษฎีที่มีความสวยงามทางคณิตศาสตร์
  - ทฤษฎีที่ดีคือทฤษฎีที่สามารถอธิบายผลการทดลองได้
  - ทฤษฎีที่ดีคือทฤษฎีที่เรียบง่ายและเข้าใจได้ง่าย
  - ทฤษฎีที่ดีคือทฤษฎีที่มีความสลับซับซ้อนและเข้าใจยาก
- อนุภาคชนิดใดบ้างต่อไปนี้ที่ไม่ถูกรวมอยู่ใน the Standard Model of Particle Physics
  - Neutrino มือซ้าย
  - Neutrino มือขวา
  - Higgs
  - Dark Matter
  - W bosons
  - GUT gauge mediators

Quiz time

- ข้อใดต่อไปนี้กล่าวถูกต้องเกี่ยวกับทฤษฎีทางฟิสิกส์
  - ทฤษฎีที่ดีคือทฤษฎีที่มีความสวยงามทางคณิตศาสตร์ ❌
  - ทฤษฎีที่ดีคือทฤษฎีที่สามารถอธิบายผลการทดลองได้ ✅
  - ทฤษฎีที่ดีคือทฤษฎีที่เรียบง่ายและเข้าใจได้ง่าย ❌
  - ทฤษฎีที่ดีคือทฤษฎีที่มีความสลับซับซ้อนและเข้าใจยาก ❌
- อนุภาคชนิดใดบ้างต่อไปนี้ที่ไม่ถูกรวมอยู่ใน the Standard Model of Particle Physics
  - Neutrino มือซ้าย ❌
  - Neutrino มือขวา ✅
  - Higgs ❌
  - Dark Matter ✅
  - W bosons ❌
  - GUT gauge mediators ✅