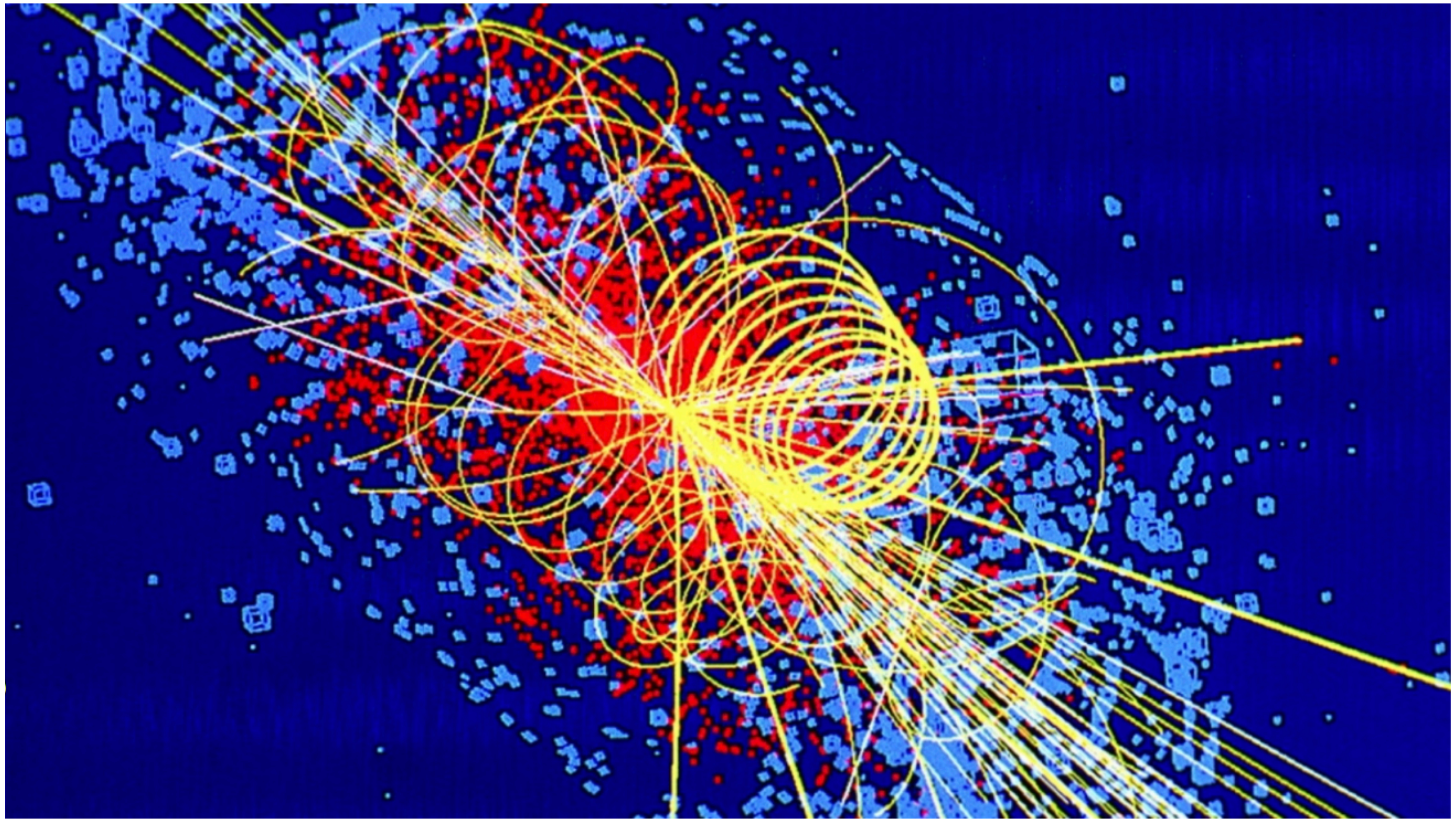
Imperial College London

Particle Physics for Non-Experts



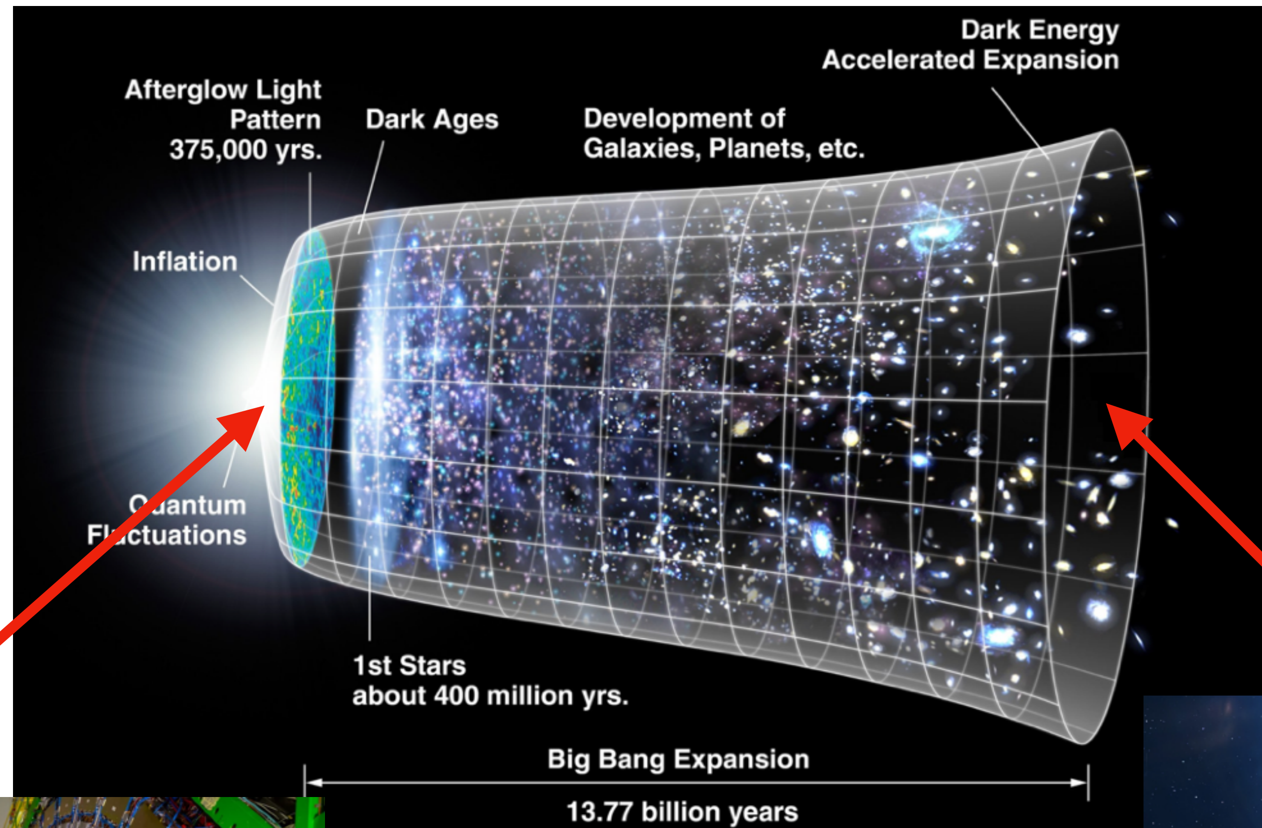
Dr Daniel Winterbottom

PHYSTAT Statistics Meets ML 2024

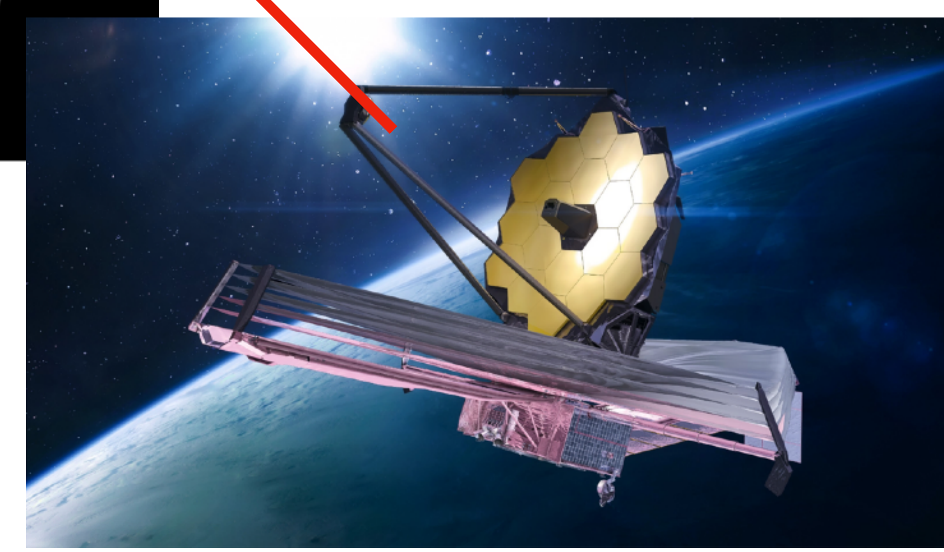
Overview

- In today's talk I will give quick overview of Particle Physics
- Overview of the Standard Model (SM) of Particle Physics
- Highlight issues with SM which we try to study
- Give a brief description of some of the latest Particle Physics experiments (not enough time for all, sorry if I missed your favourite one!)
- Talk is intended for non-particle physicists

- Understand the Universe from the Big Bang to the star and galaxies we see today, and predict how it will look in the future



Particle observatory e.g LHC

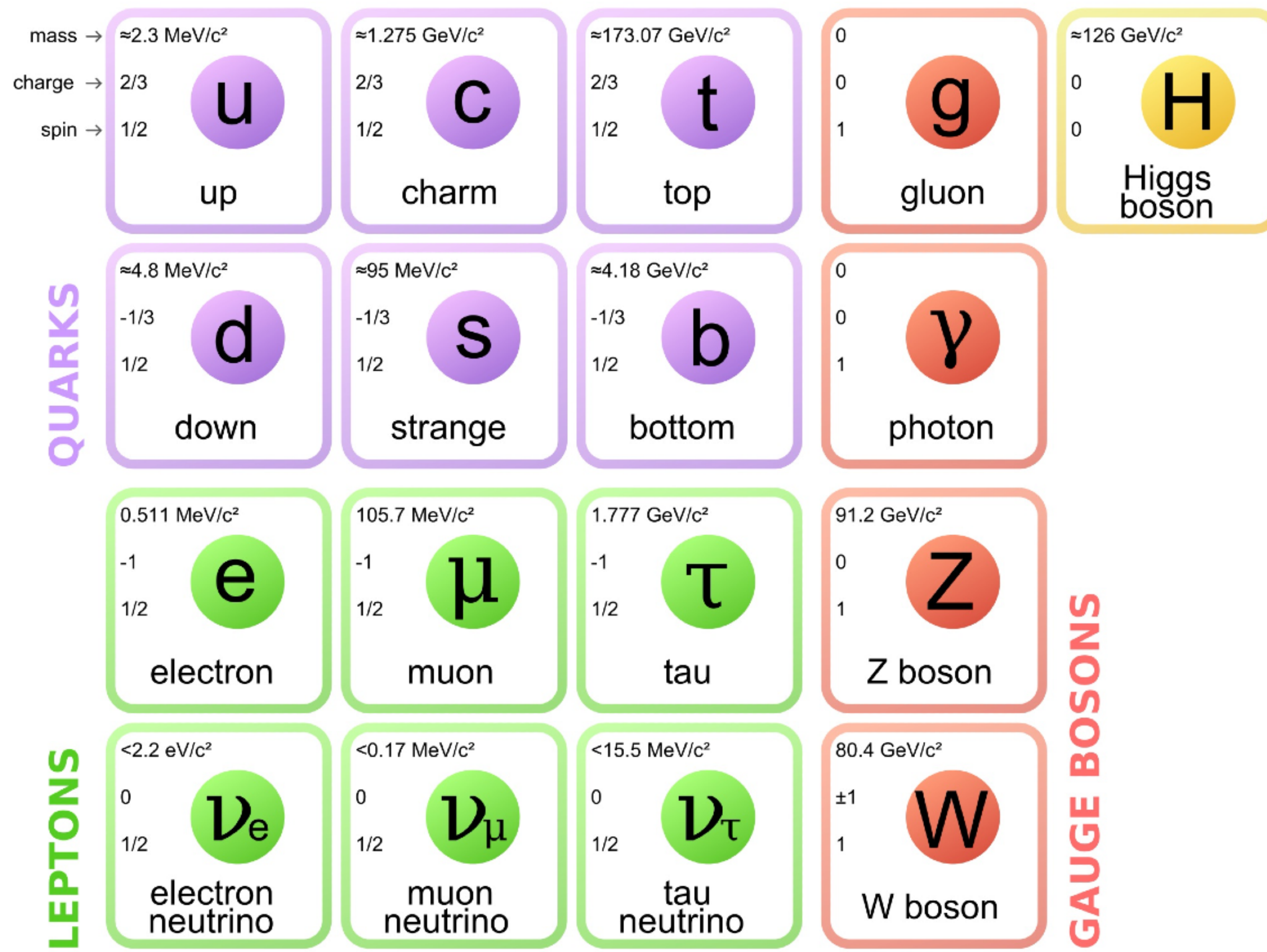


Astronomical observatory e.g James Webb

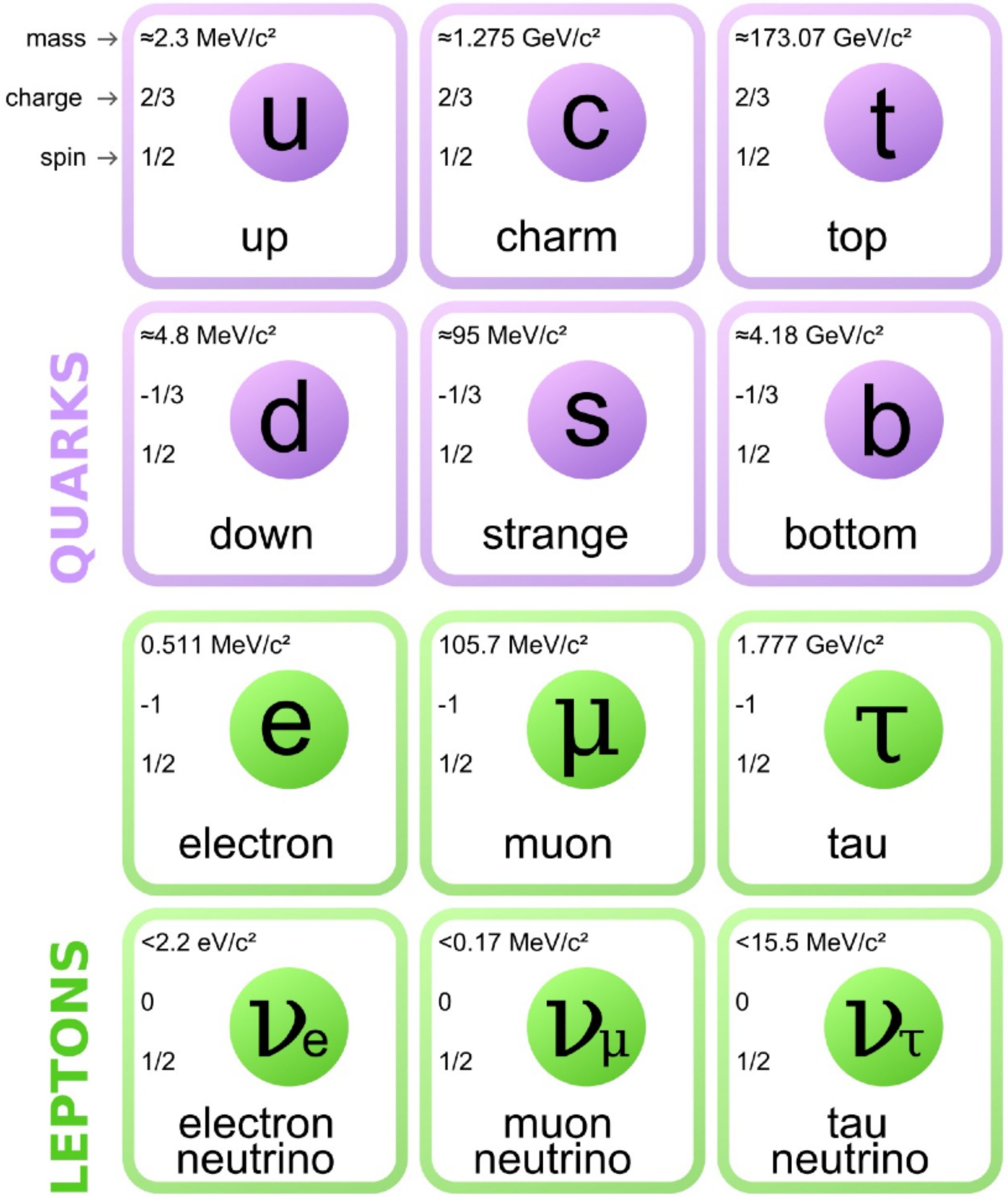
The Standard Model of particle physics

- A “periodic table” of the fundamental building blocks of the Universe

- Also described how they interact with each other via electromagnetic, strong-nuclear, and weak-nuclear forces



Fermions

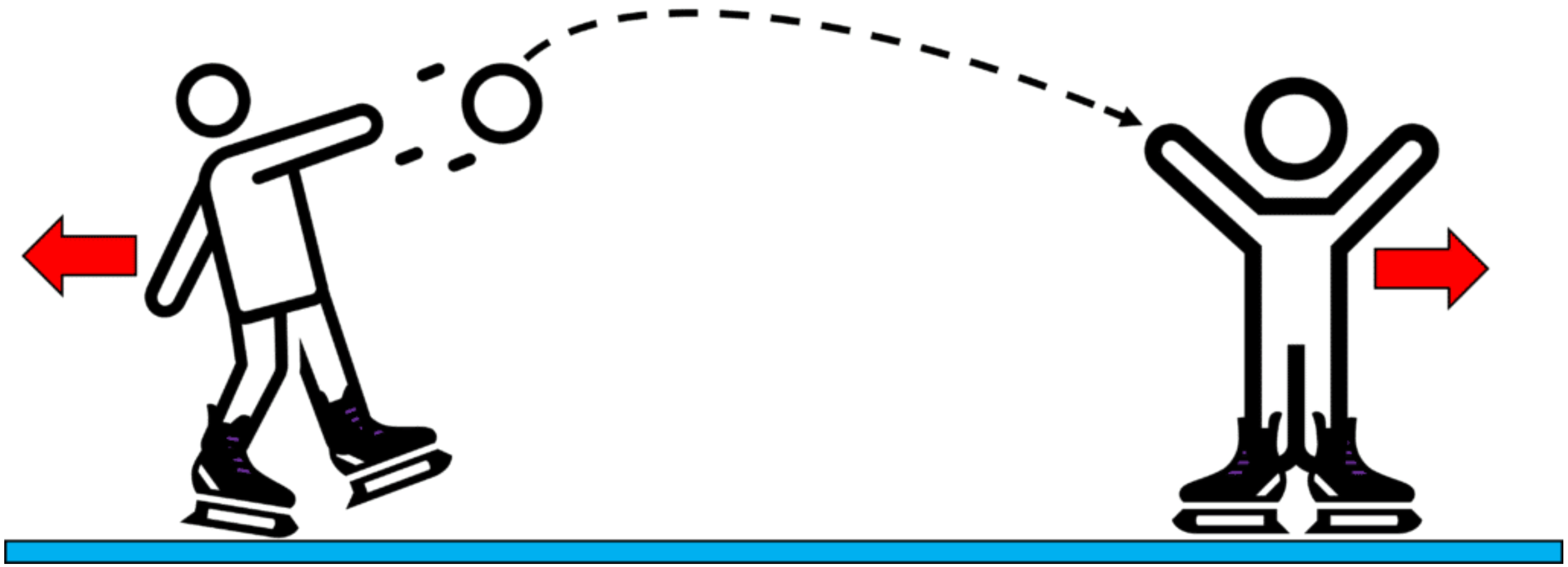


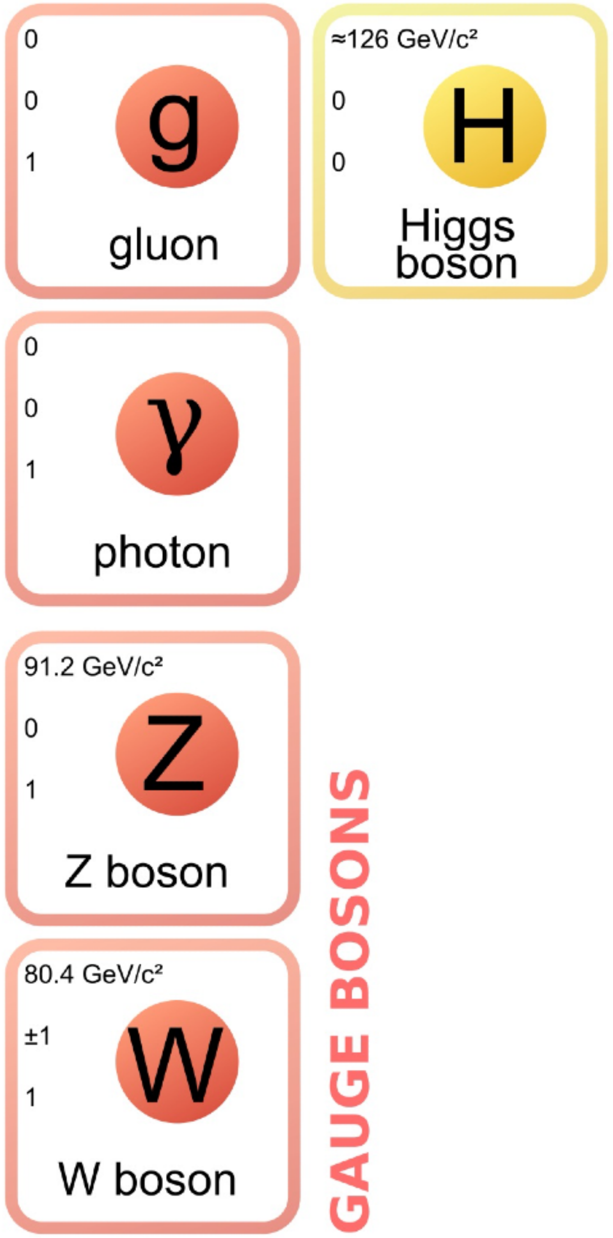
- The quarks are subatomic particles that make up hadrons such as protons (uud) and neutrons (ddu)
- Charged leptons i.e the electron and heavier cousin the muon and tau leptons
- Neutral leptons - neutrinos, very weakly interacting
- Three copies or “generations” (we don’t know why)

Bosons

- Bosons include force carriers (spin-1) and Higgs boson (spin=0)

- Force carriers mediate the interactions in the SM though the exchange of virtual particles





- Higgs boson related to origin of mass - more later!

The forces

- The strong force:
  Binds quarks together to form hadrons
  Mediated by the gluon, g

- Electromagnetism:
  Responsible for attraction and repulsion of electrically charged particles
  Mediated by the photon, γ

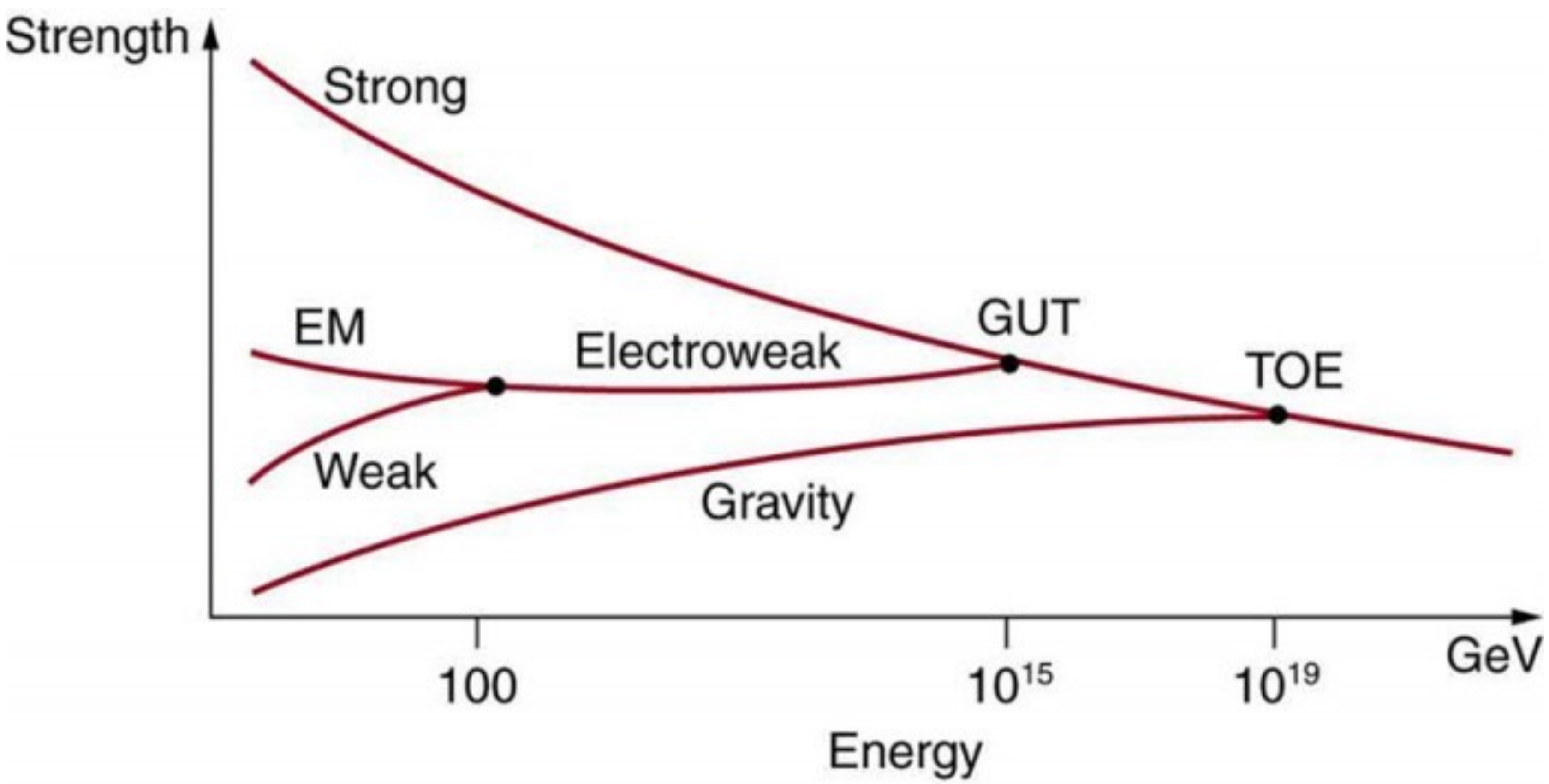
- The weak force:
  Responsible for radioactive beta decay
  Mediated by the $W^{\pm}$ and Z bosons

Gravity not in the SM
Mediated by gravitons?

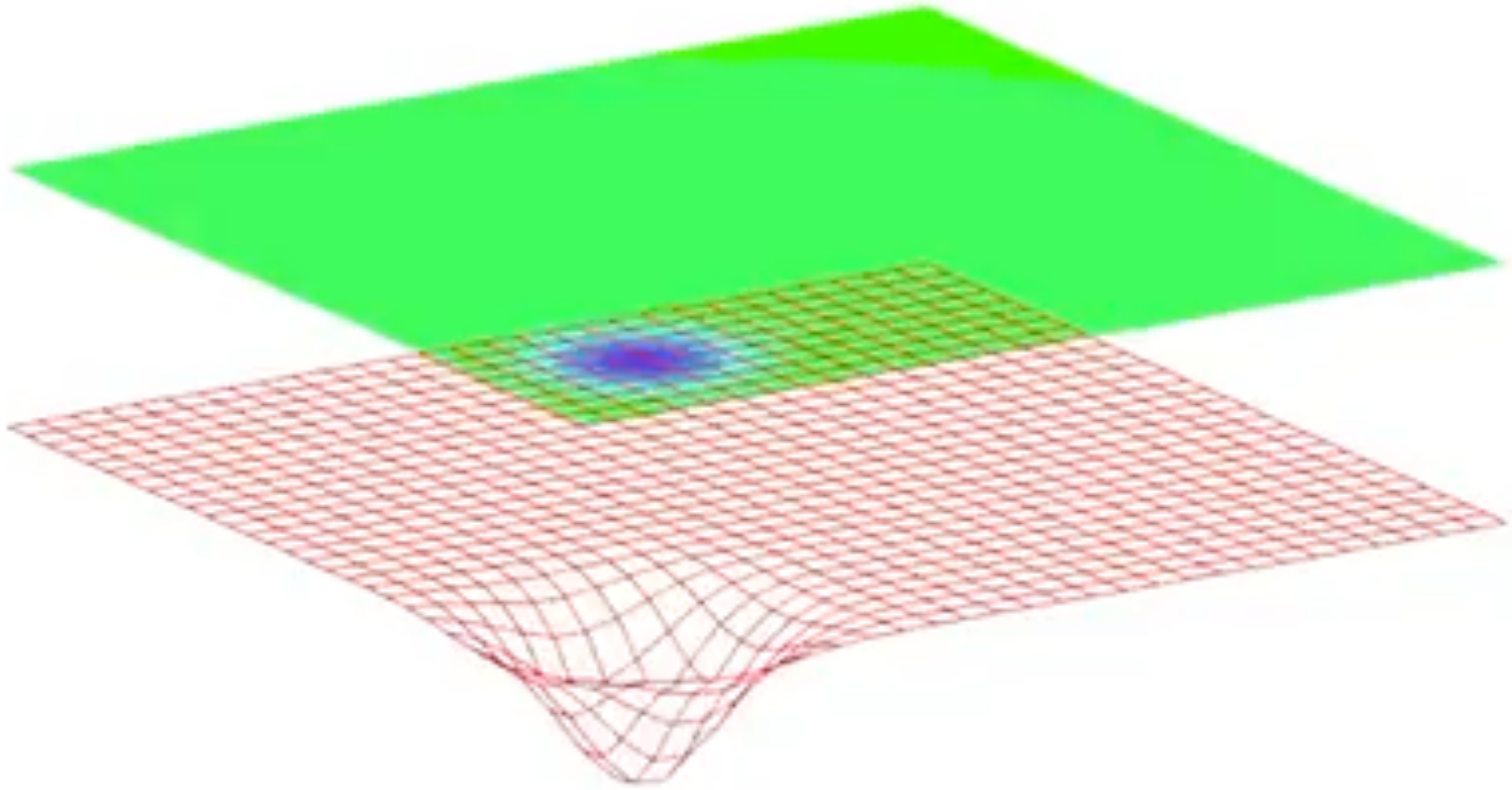
Weaker

Unification of the forces

- Weak and electromagnetic forces were shown to be manifestation of same force (electroweak force) - different couplings strengths due to masses of W and Z
- Can we unify other forces?
- Grand Unified Theory (GUT) = unification of electroweak and strong forces
- Theory of Everything (TOE) unifies also gravity
- Couplings run with energy and hopefully intersect at high energies



- Quantum field theory describes particles as excitations ("ripples") in fields that permeate all of space and time
- e.g a photon is excitation of the electromagnetic field



Gauge Theories

- Gauge theories explain forces by imposing symmetries on the equations of motion
- A gauge transformation is a change of variables that leaves the physical predictions of a theory unchanged (gauge invariant)
- E.g classical electromagnetism: $\phi \rightarrow \phi' = \phi + \frac{\partial f}{\partial t}$, $A \rightarrow A' = A - \nabla f$ does not change observable E and B fields
- Gauge transformation of the free electron wave function: $\psi(\mathbf{r},t) \rightarrow \psi'(\mathbf{r},t) = e^{ief(\mathbf{r},t)}\psi(\mathbf{r},t)$

In QED we demand the equations of motion to be gauge invariant

Not gauge invariant

$$i\frac{\partial \psi}{\partial t} = -i\alpha \cdot \nabla \psi + \beta m \psi$$

$$\neq$$

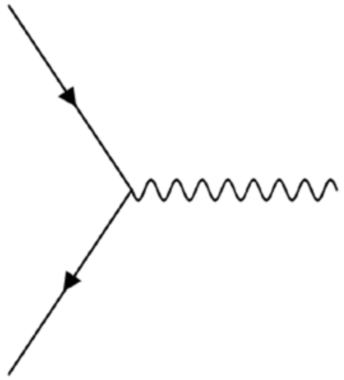
$$i\left(\frac{\partial}{\partial} - ie\frac{\partial f}{\partial t}\right)\psi = -i\alpha \cdot \left(\nabla - ie\nabla f\right)\psi + \beta m \psi$$

This requires adding pieces to the equation This corresponds to a force

Gauge invariant

$$i\left(\frac{\partial}{\partial t} - ie\phi\right)\psi = -i\alpha \cdot (\nabla + ieA)\psi + \beta m \psi$$

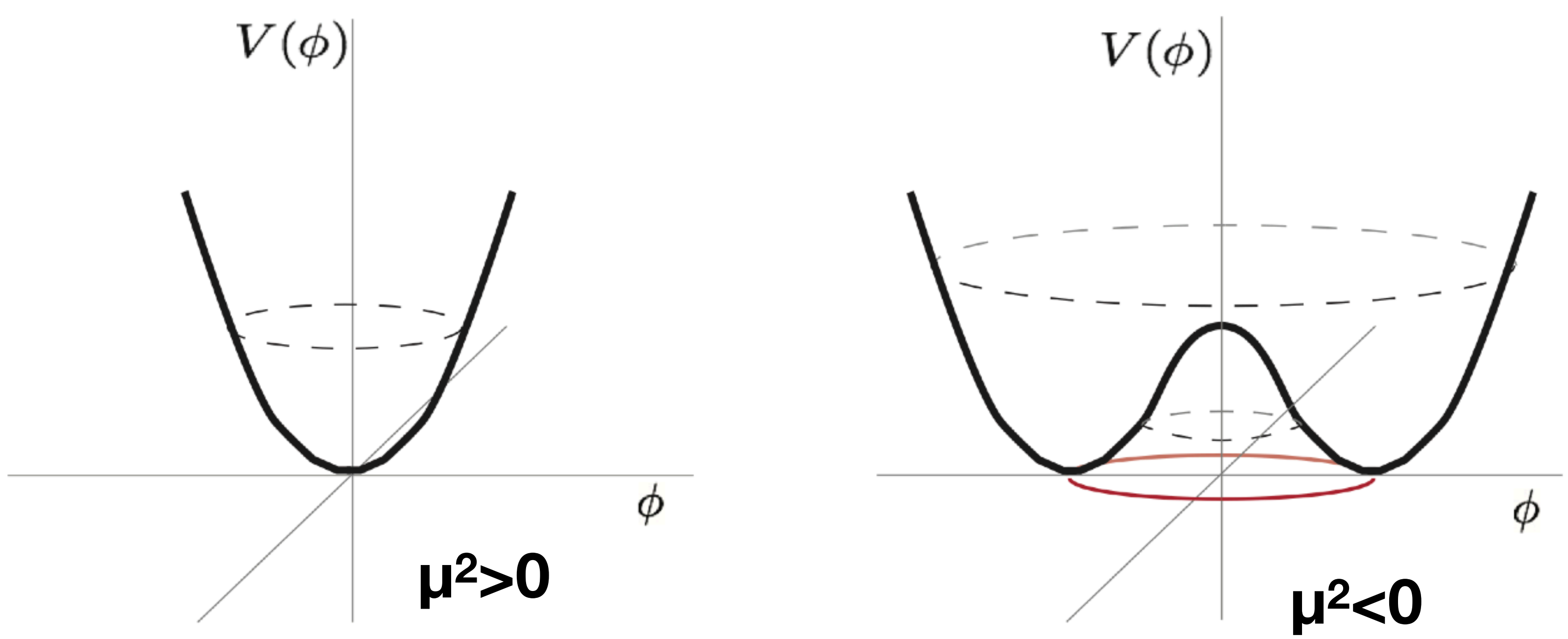
These terms correspond to interactions between the charged fermions and the photon field



Spontaneous symmetry breaking

- Given success of QED theorists tried to make a gauge theory of the weak force
- But gauge symmetry requires $W^{\pm}$ and Z to be massless
  - m_W ~ 80 GeV, m_Z ~ 90 GeV
- In 1960s, Higgs mechanism predicted as generator of mass
- The Higgs mechanism introduces a field ϕ (the Higgs field) with potential V(ϕ) that is symmetric
- Above T_c ground state is also symmetric
- Below T_c ground state not symmetric anymore, non-zero vacuum expectation value (vev) = 246 GeV

$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda(\phi^\dagger \phi)^2$$

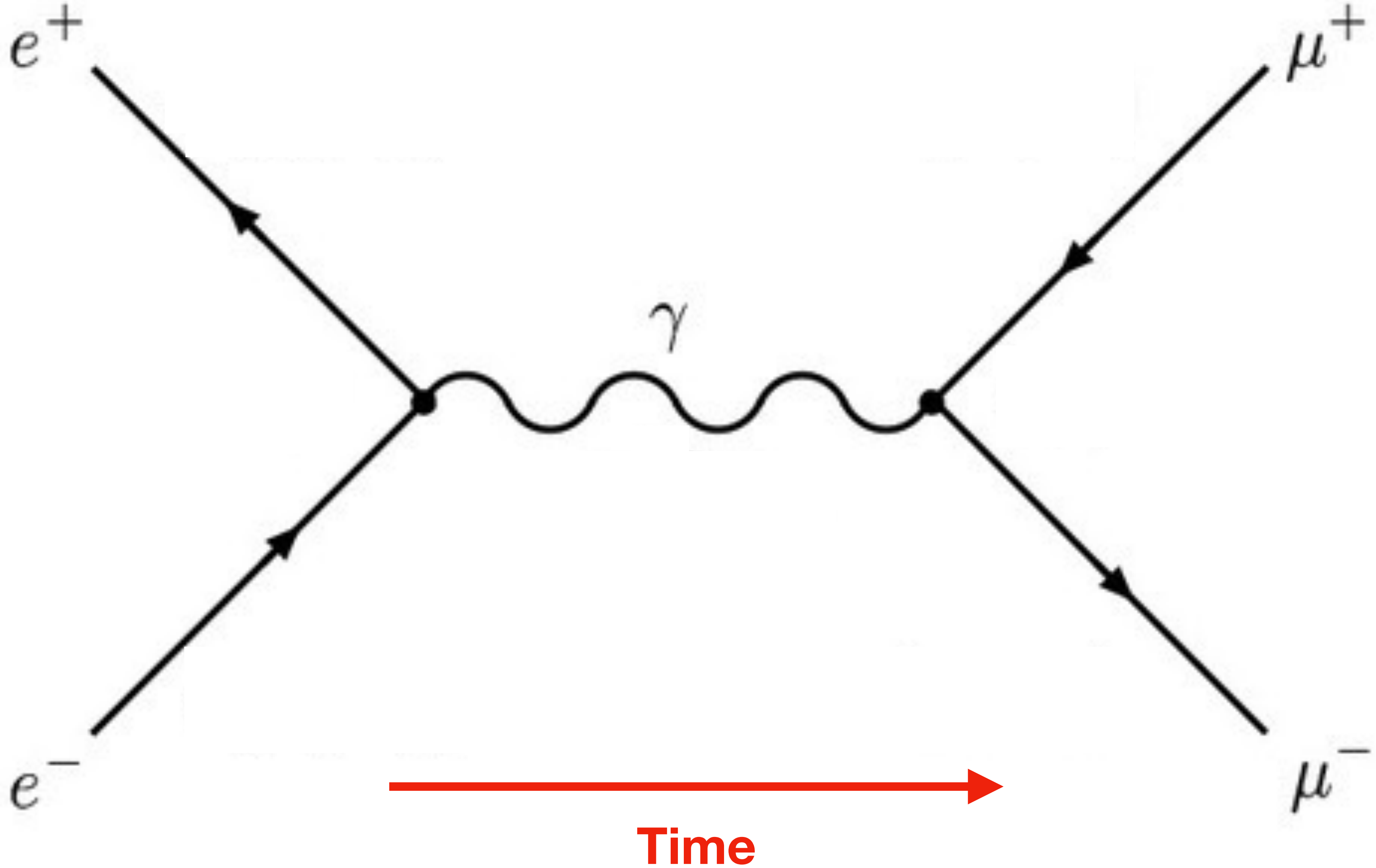


The Higgs mechanism

- Non-zero vev makes the vacuum “sticky”
- Particles moving through it interact with the vev and feel inertia i.e mass
- If we collide particles hard enough they can cause **ripples** in the Higgs field
    - The Higgs bosons that we can detect!

Feynman diagrams

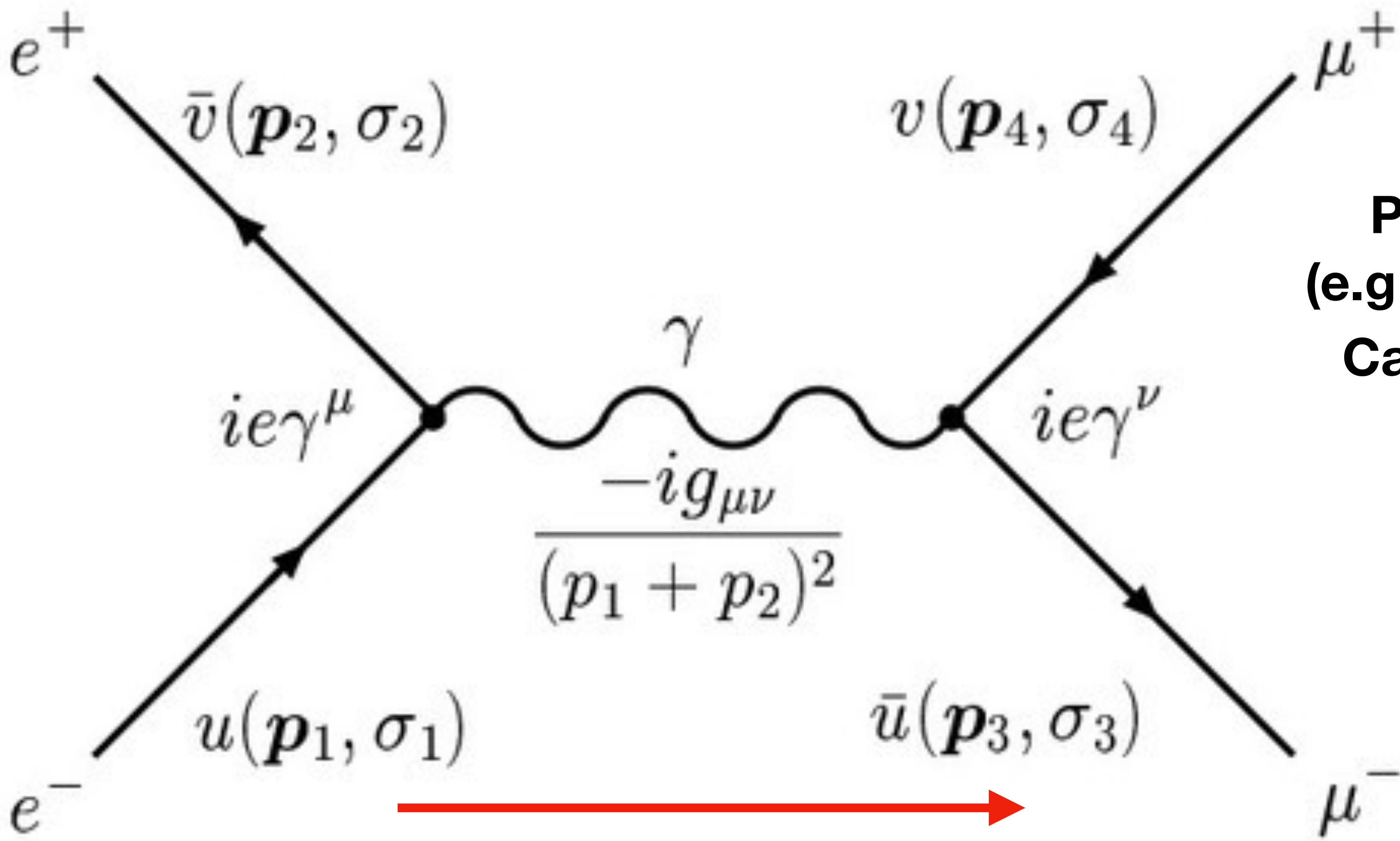
- Feynman diagrams give a pictorial way of visualising particle interactions



Feynman diagrams

- But also encode important information about the amplitude computation

- Each line and vertex represents an expression (“Feynman rules”), and product of expressions used to compute the probability amplitude

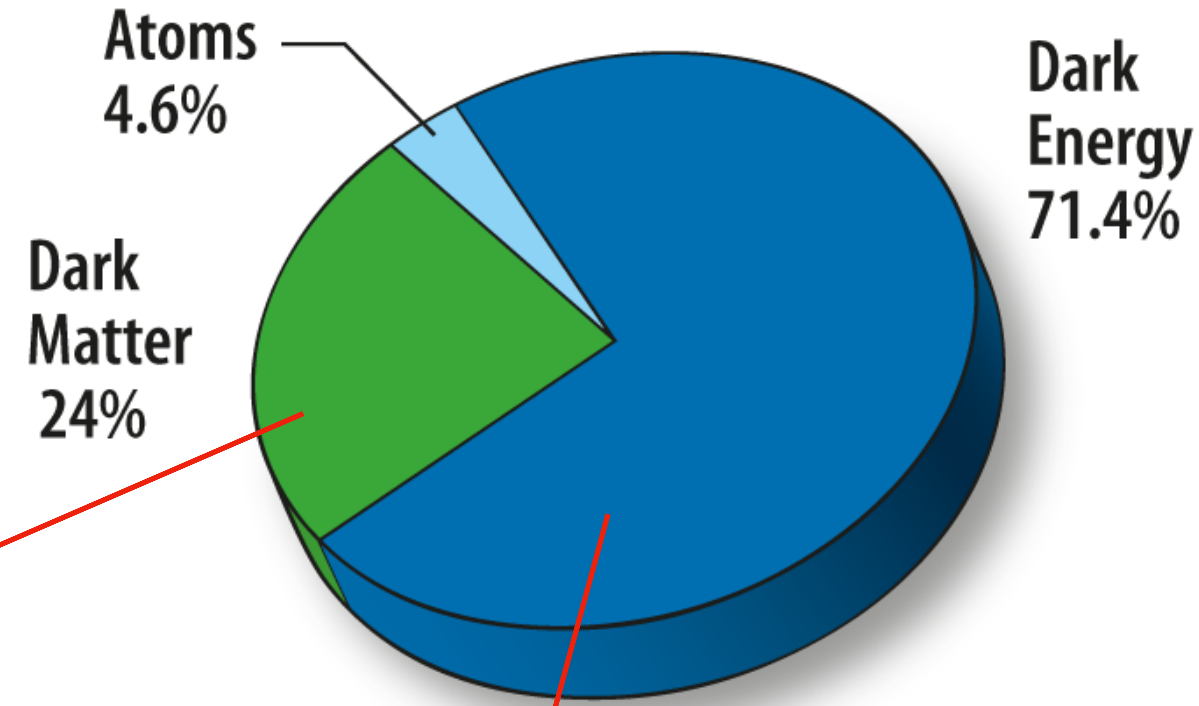


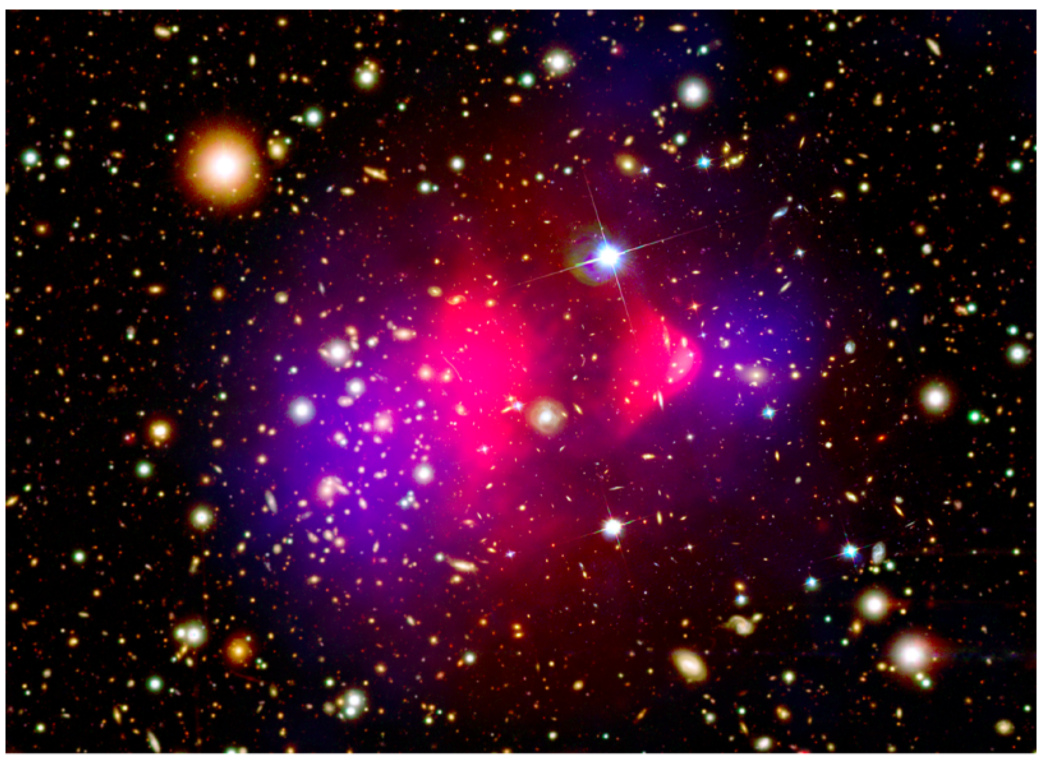
Time

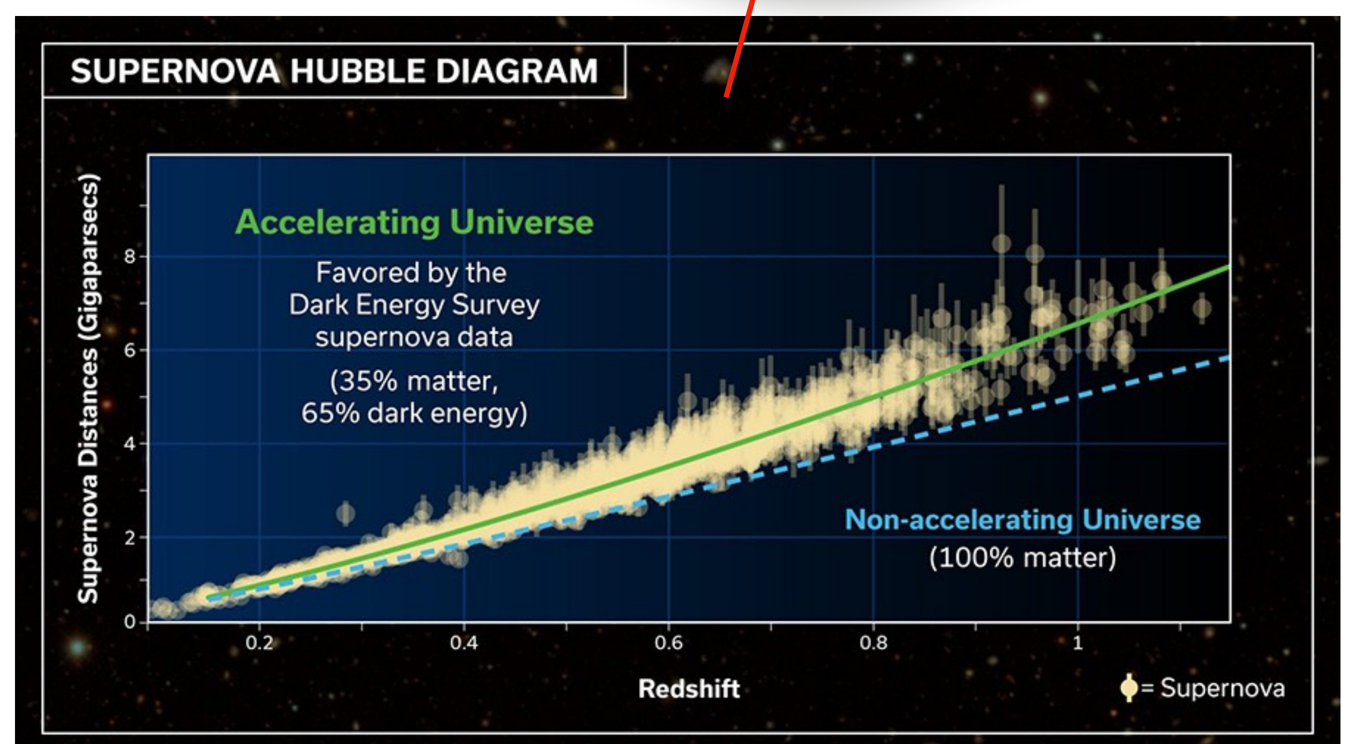
Propagators (p)
(e.g γ in left diagram)
Can be “off-shell”
$E^2 - p^2 \,!= m_p^2$

- We don't know what 95% of the Universe is: dark matter and dark energy

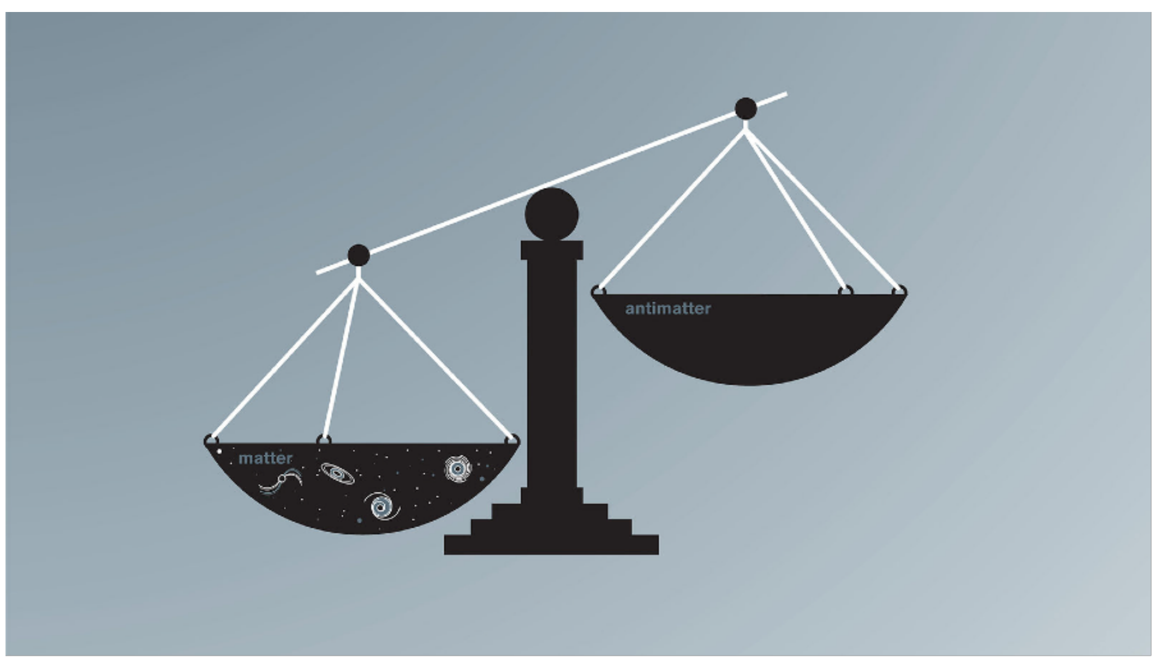
- Dark matter may be a new particle?

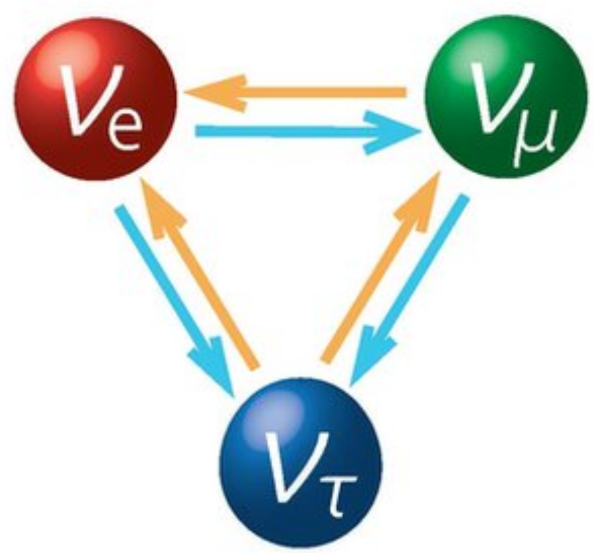


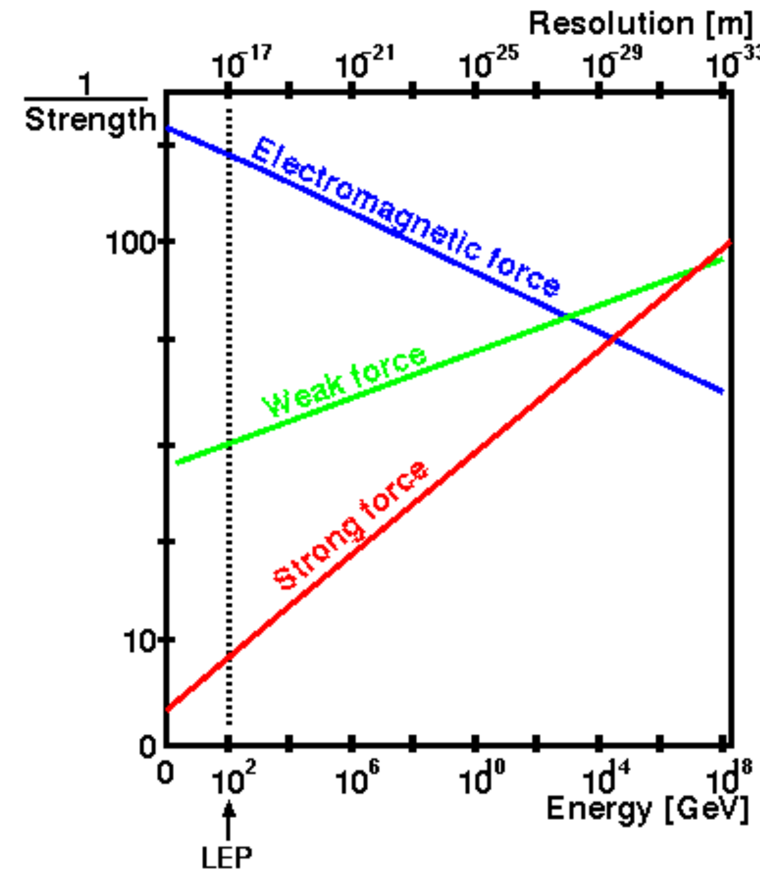




- Why the Universe there is so much more matter than anti-matter
- Neutrinos are massless in the SM but neutrino oscillations show that they must have some mass
- Coupling strengths for strong, weak, and electro-magnetic forces do not intersect at high energies as expected in a Grand Unified Theory (GUT)

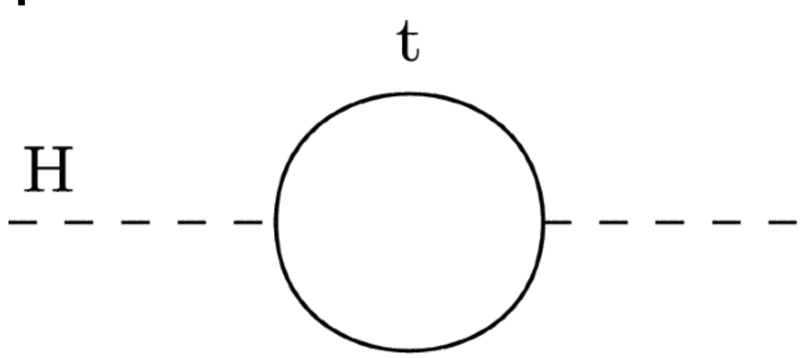






What we don't know: the Hierarchy Problem

- Higgs mass receives loop corrections from every particle that couple directly or indirectly to it



- The size of this correction is

$$\Delta m_{\mathrm{H}}^2 = -\frac{y_f^2}{8\pi^2}\Lambda^2 + \ldots$$

Where $\Lambda \sim O(10^{19})$

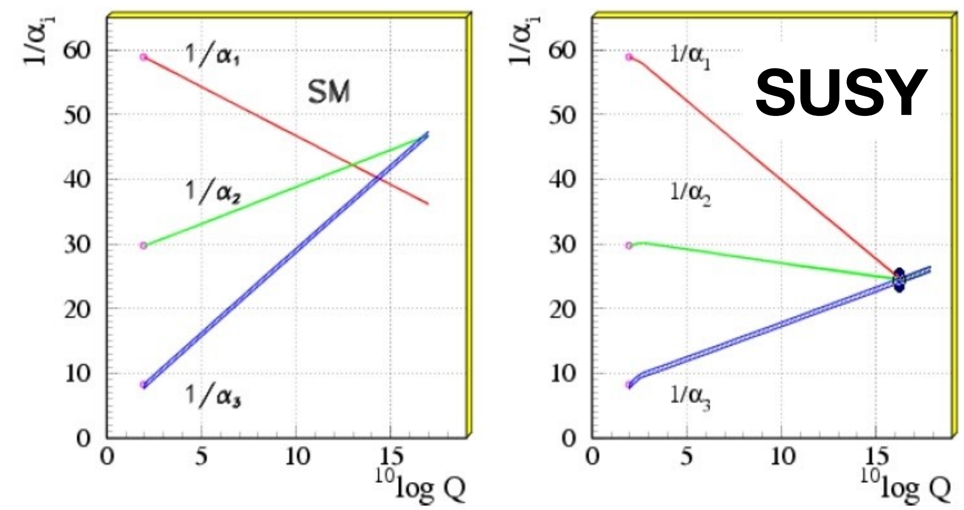
- The observed Higgs boson mass (125 GeV) can be achieved by fine tuning of the base mass

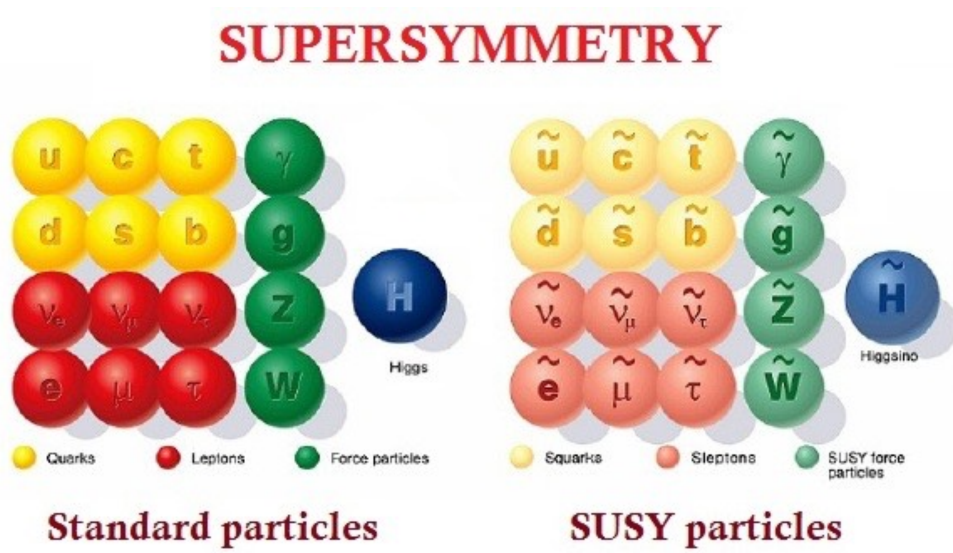
$$m_{\mathrm{H}}^2 = m_{\mathrm{H}}^{0\;2} + \Delta m_{\mathrm{H}}^2.$$

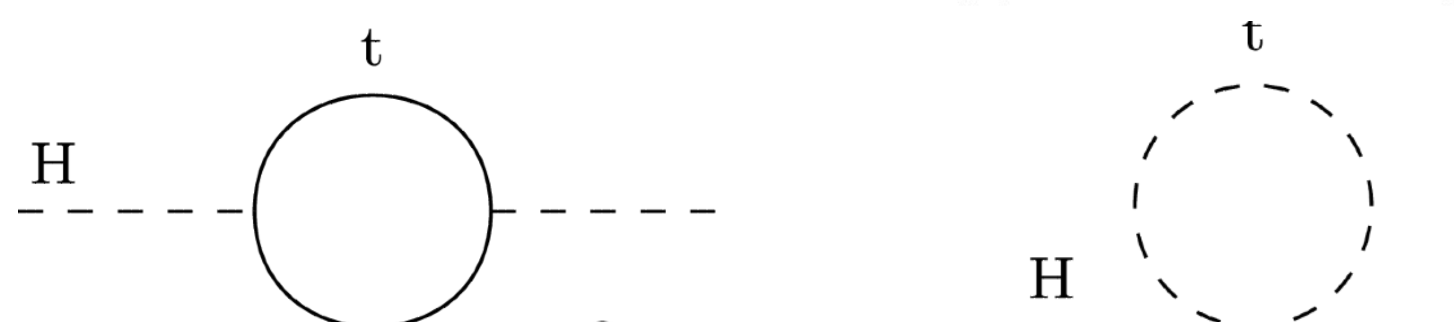
- But such a fine tuning seems unnatural

Supersymmetry?

- Fundamental symmetry that links fermions and bosons
- Solves hierarchy problem
- Also gives dark matter candidate (lightest SUSY particle)
- Makes couplings intersect at high energy







$$\Delta m_{\mathrm{H}}^2 = -\frac{y_f^2}{8\pi^2}\Lambda^2 + \frac{\lambda_S}{8\pi^2}\Lambda^2 + \ldots,$$

Supersymmetry?

- Issue: We expected to see SUSY partners at LHC already and we didn't..

- SUSY not completely dead but less favoured

- Other ideas?

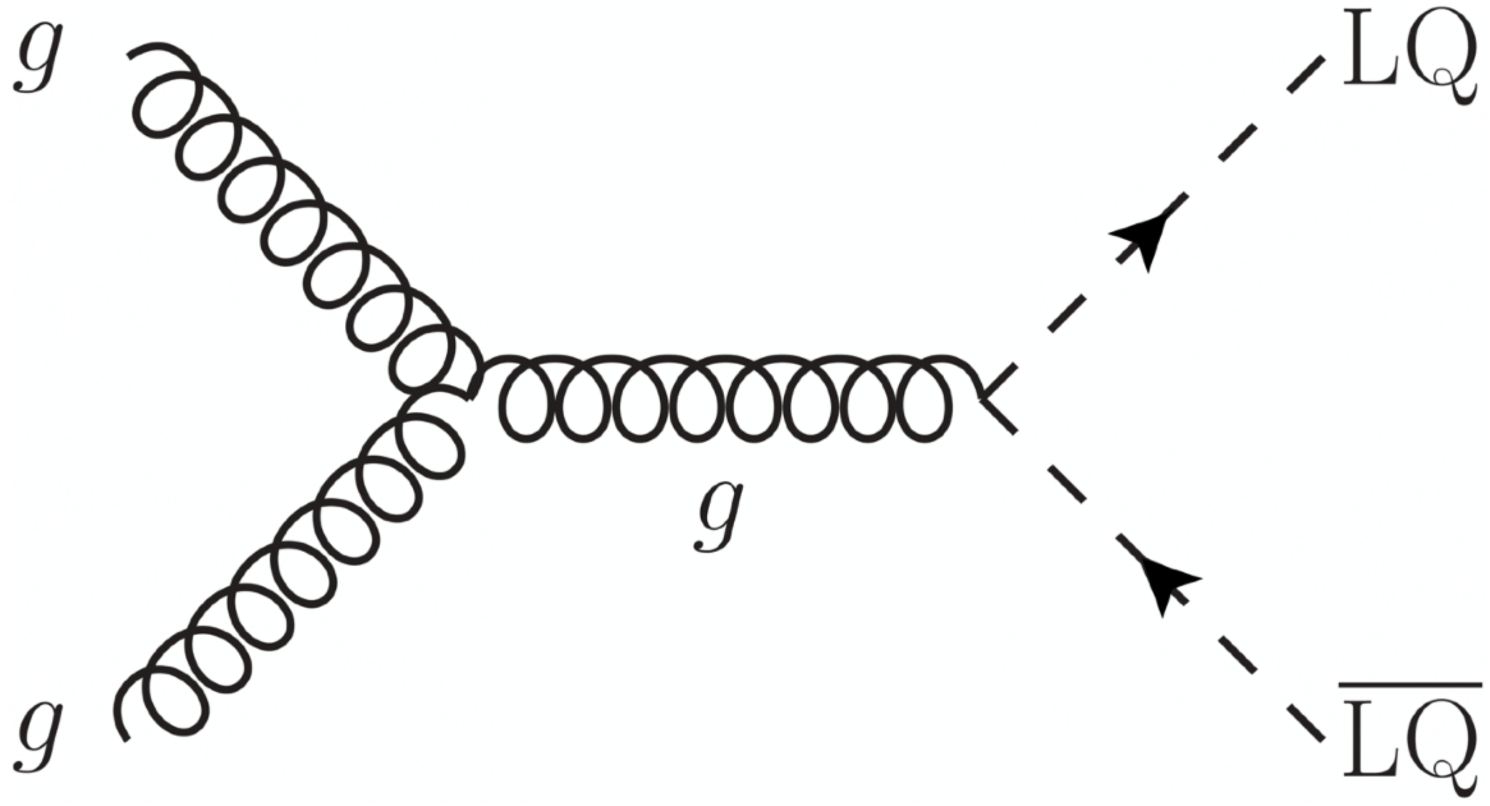
  - Hierarchy problem - composite Higgs?

  - Dark matter - inert Higgs bosons? Hidden dark sectors?

- Alternatives also predict new particles that we can search for

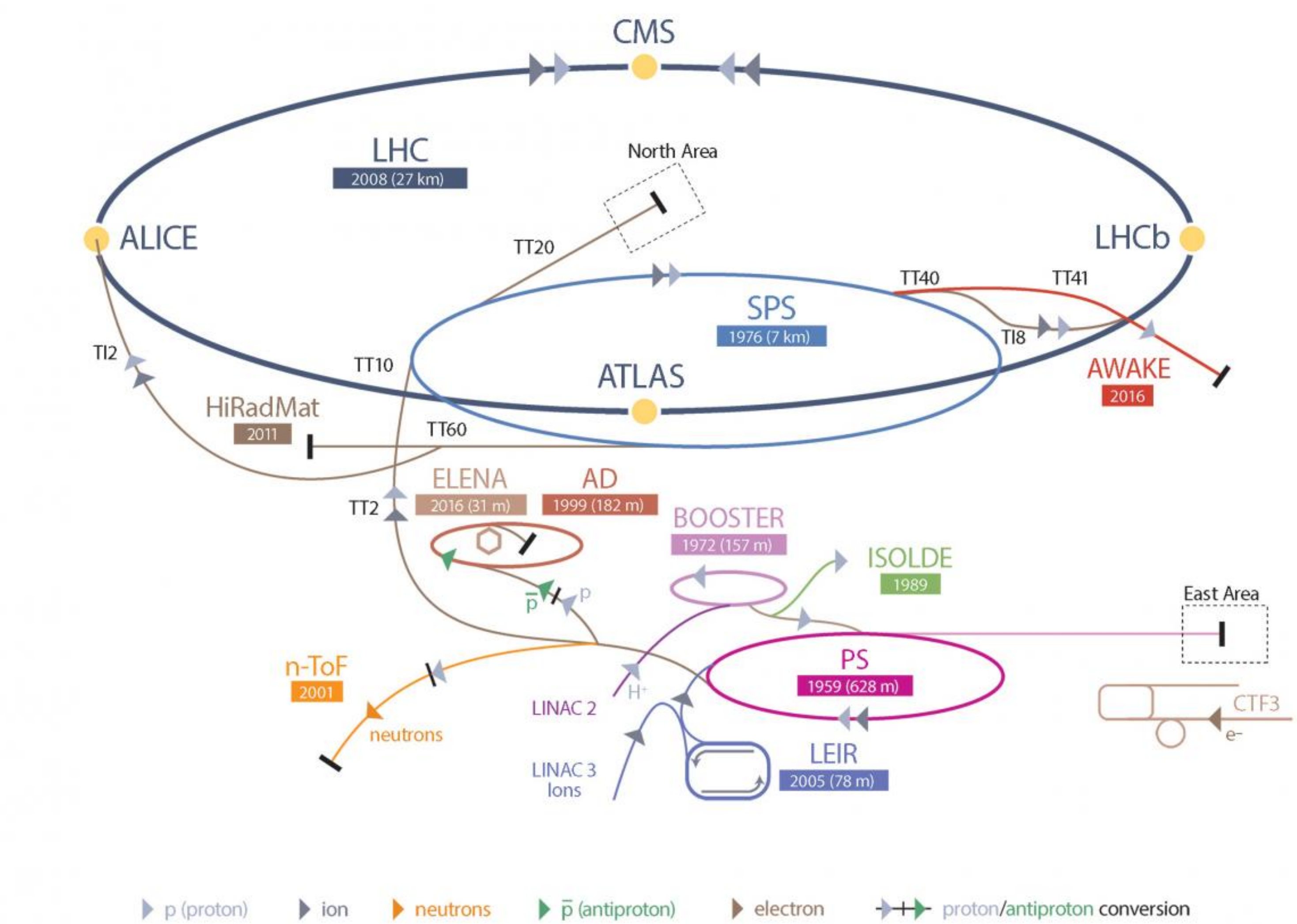
Produce new particles directly

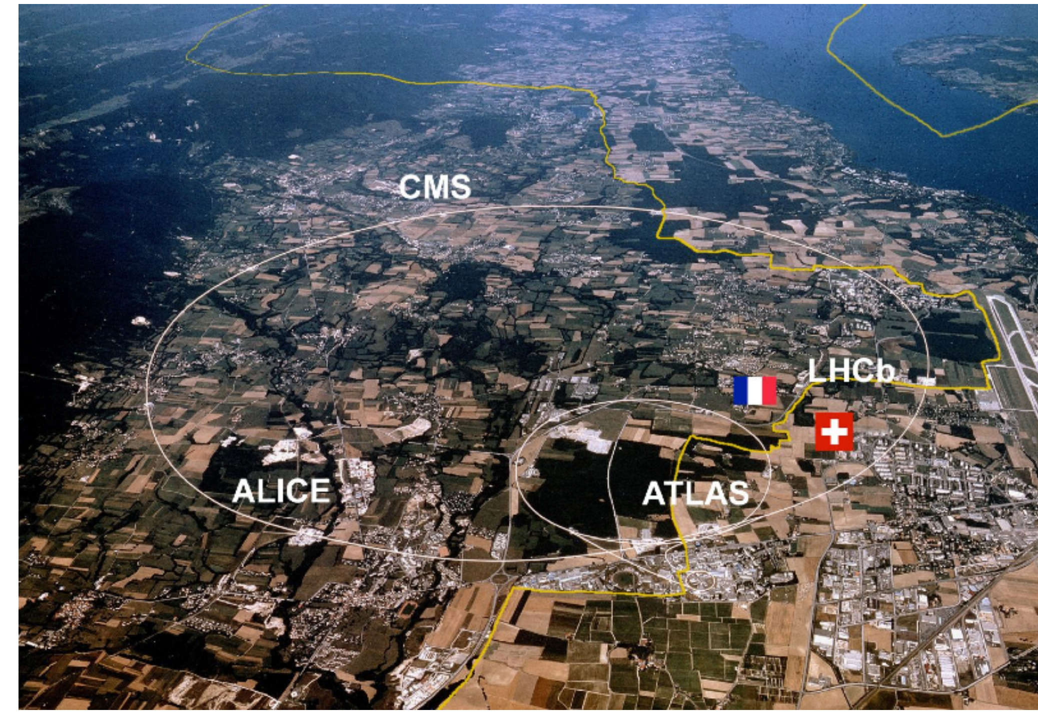
- If we can collide particles at high enough energies we can produce new heavy particles directly (on-shell) - high-energy frontier



The current high-energy particle accelerator

- The Large Hadron Collider (LHC)
- Largest most energetic collider to date
- Collides protons at energy of 13.6 TeV





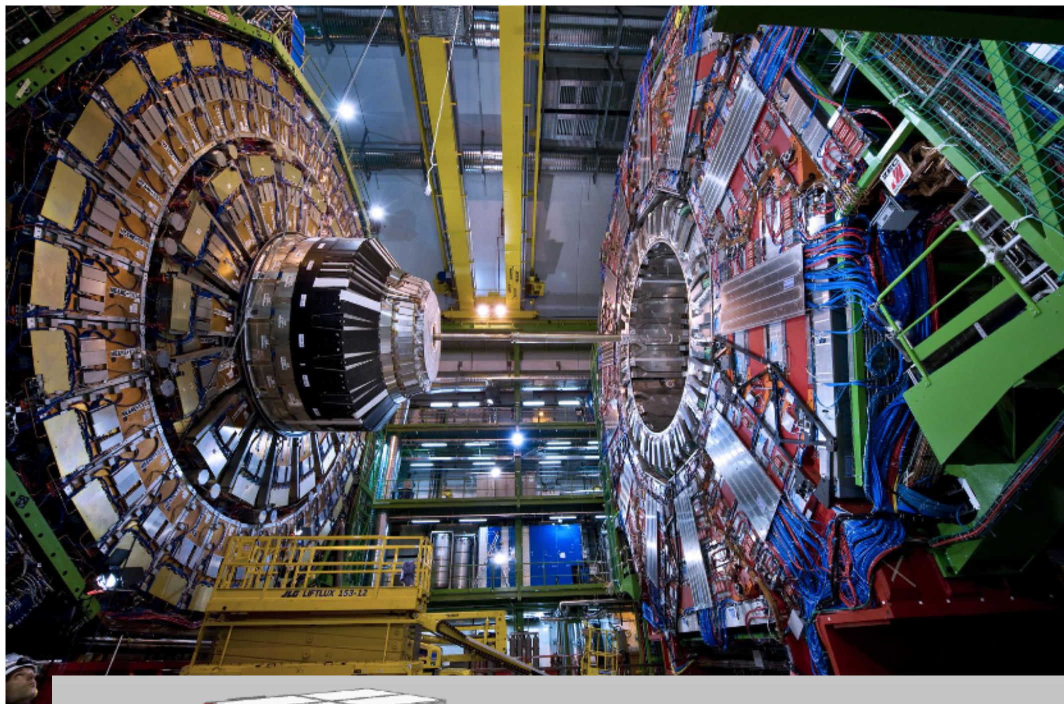
Large = 27 km ring

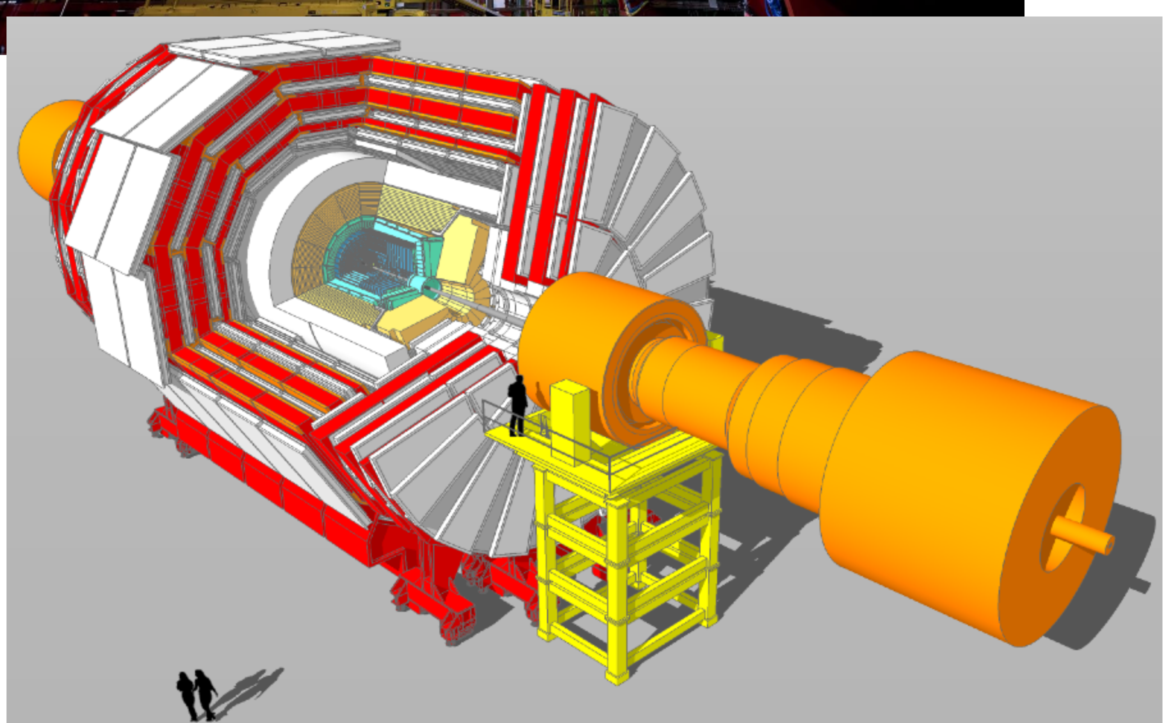
Hadron = accelerate protons (hadron) to almost the speed of light

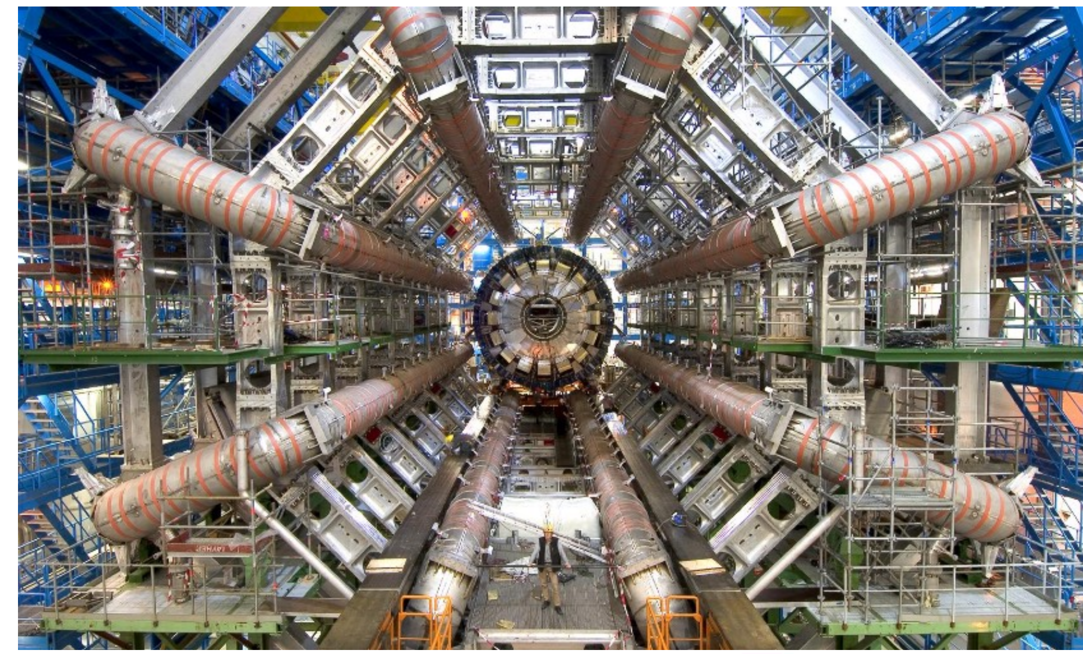
Collider = two proton beams collide 40 millions times a second

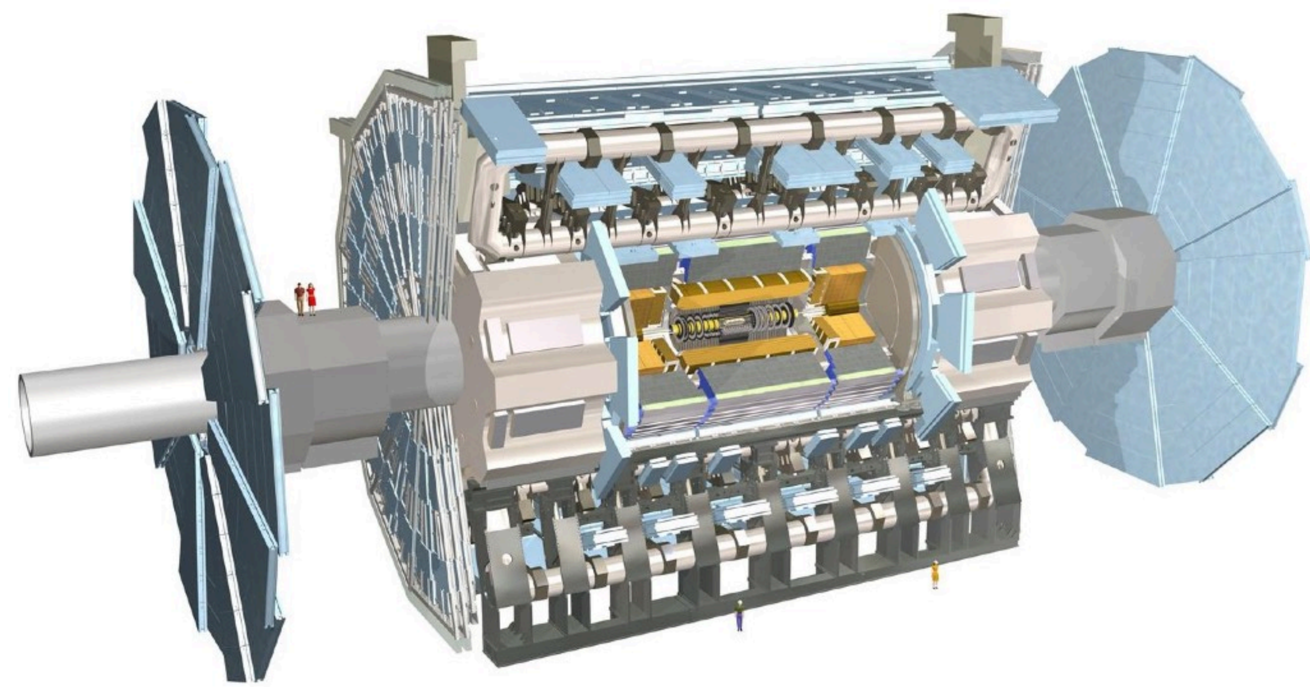
The CMS an ATLAS experiments

- LHC has four p-p interaction points
- Two general purpose experiments: CMS and ATLAS

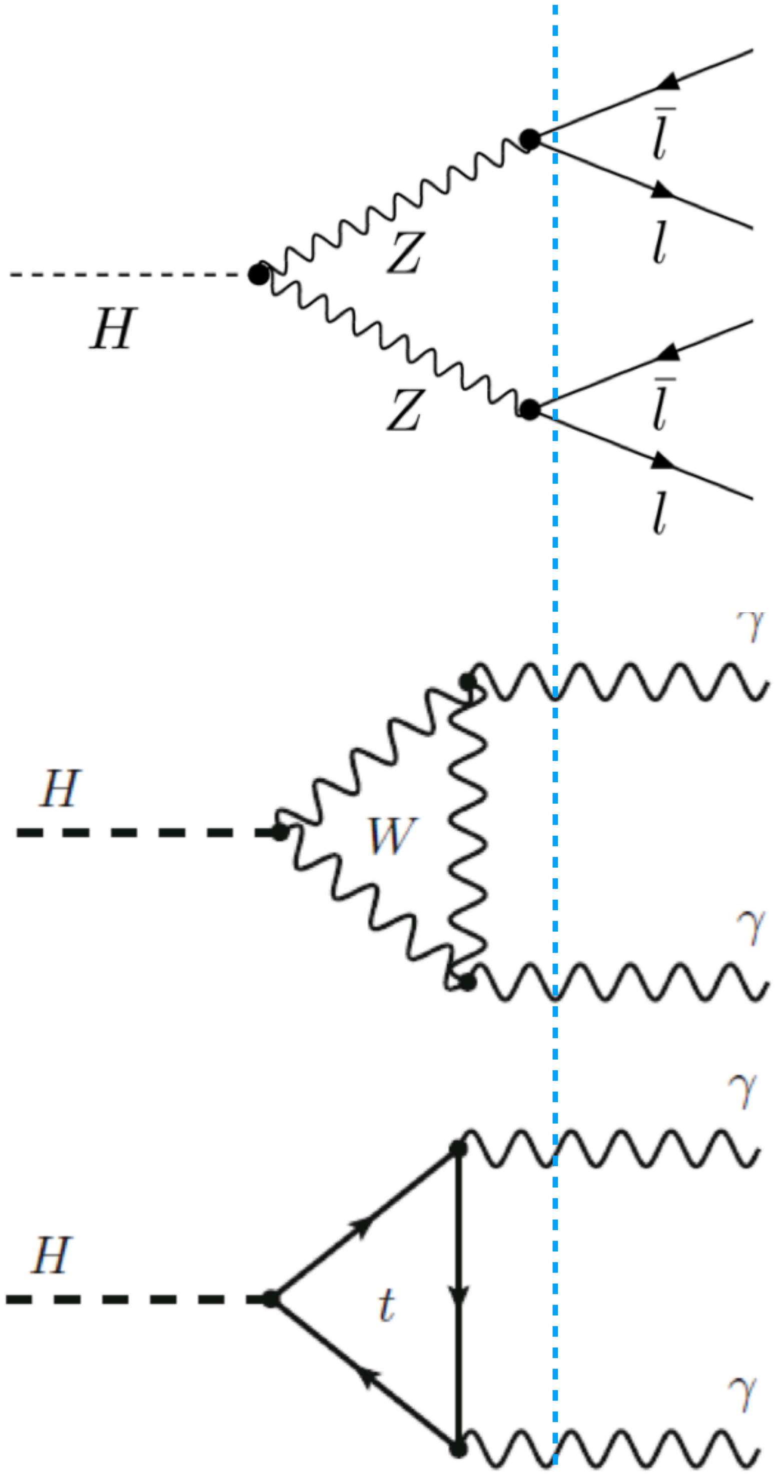


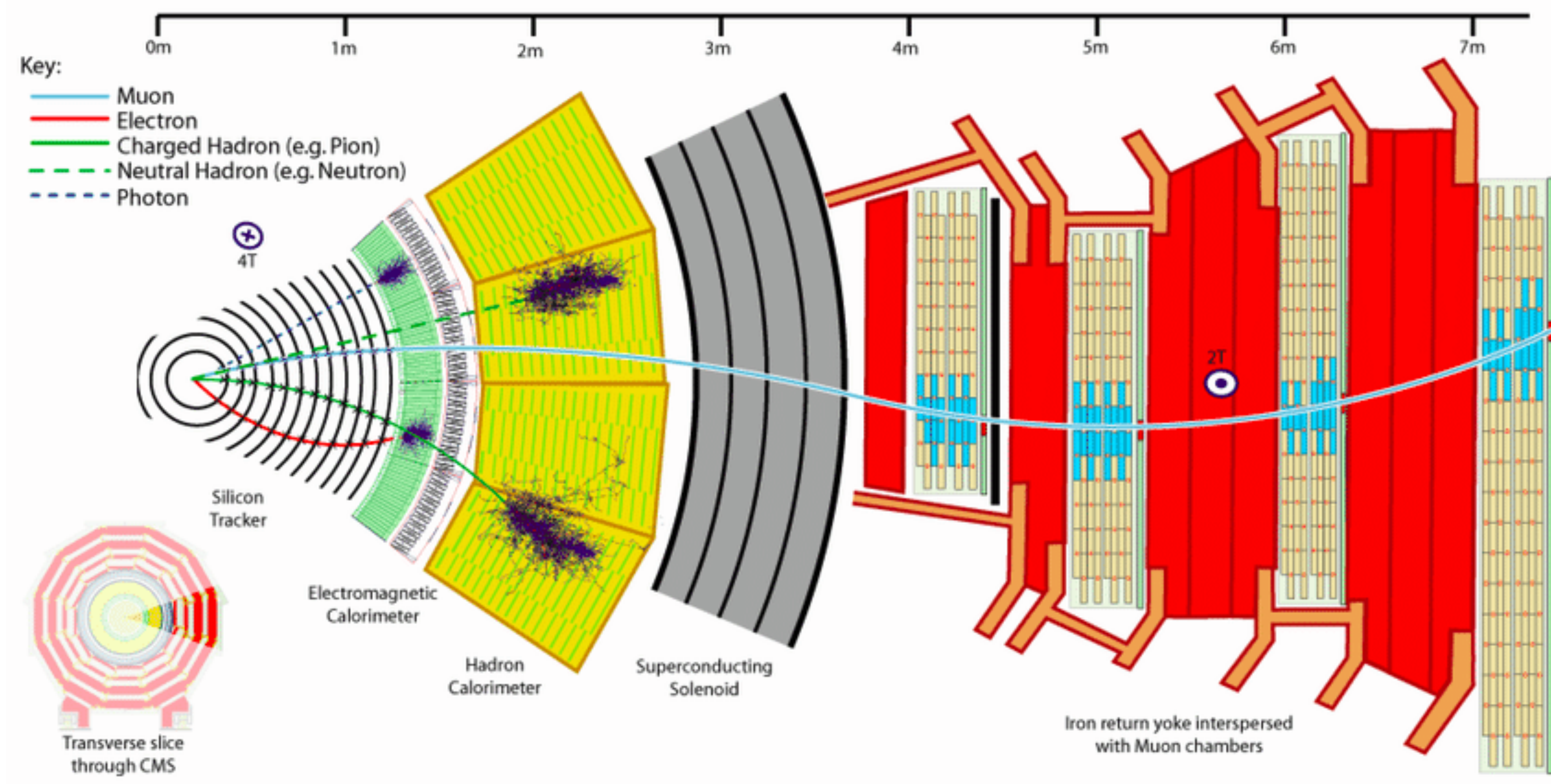






Detecting particles with CMS





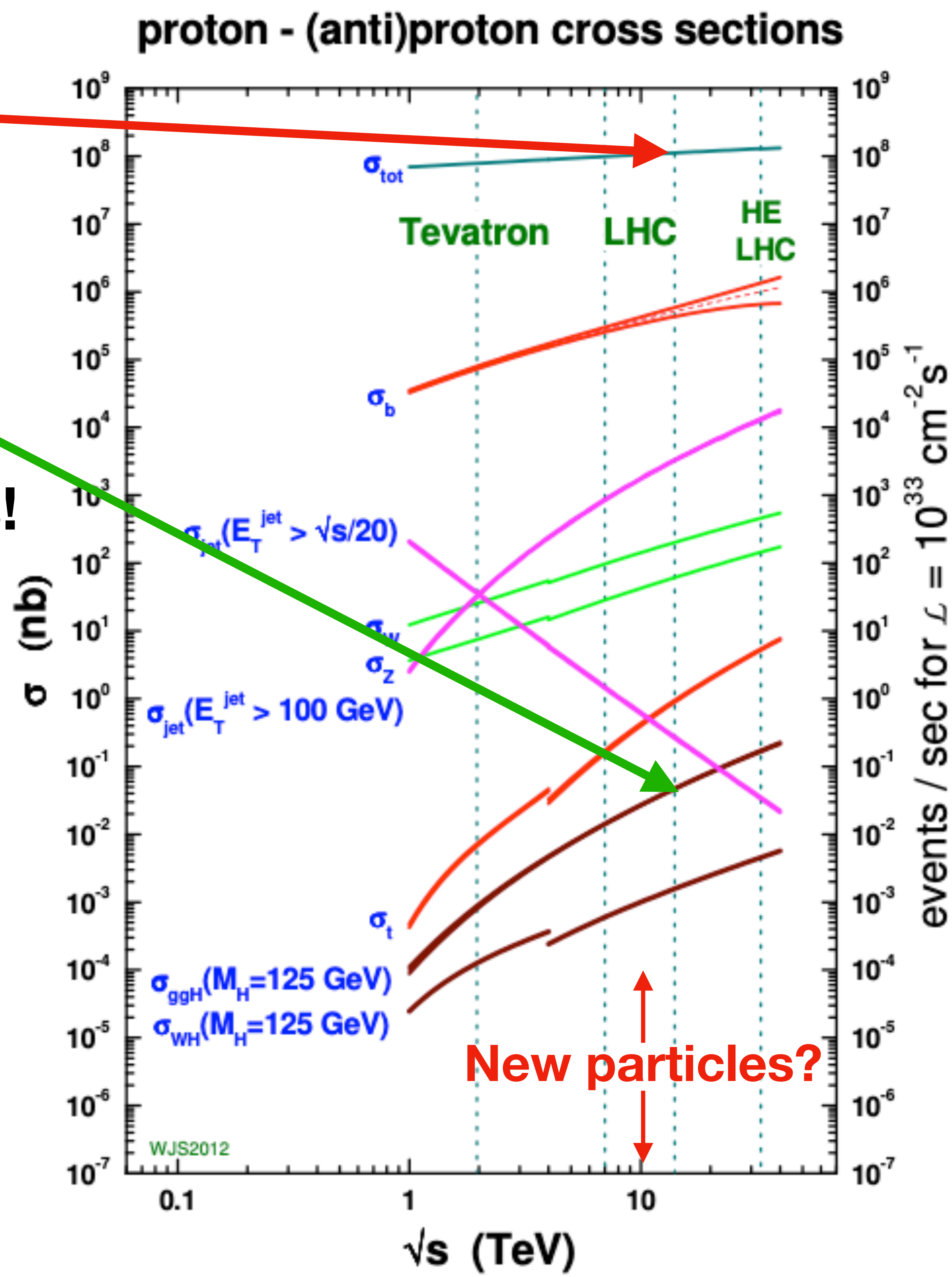
What we want to measure

What we see in the detector

This is our total p-p cross-section

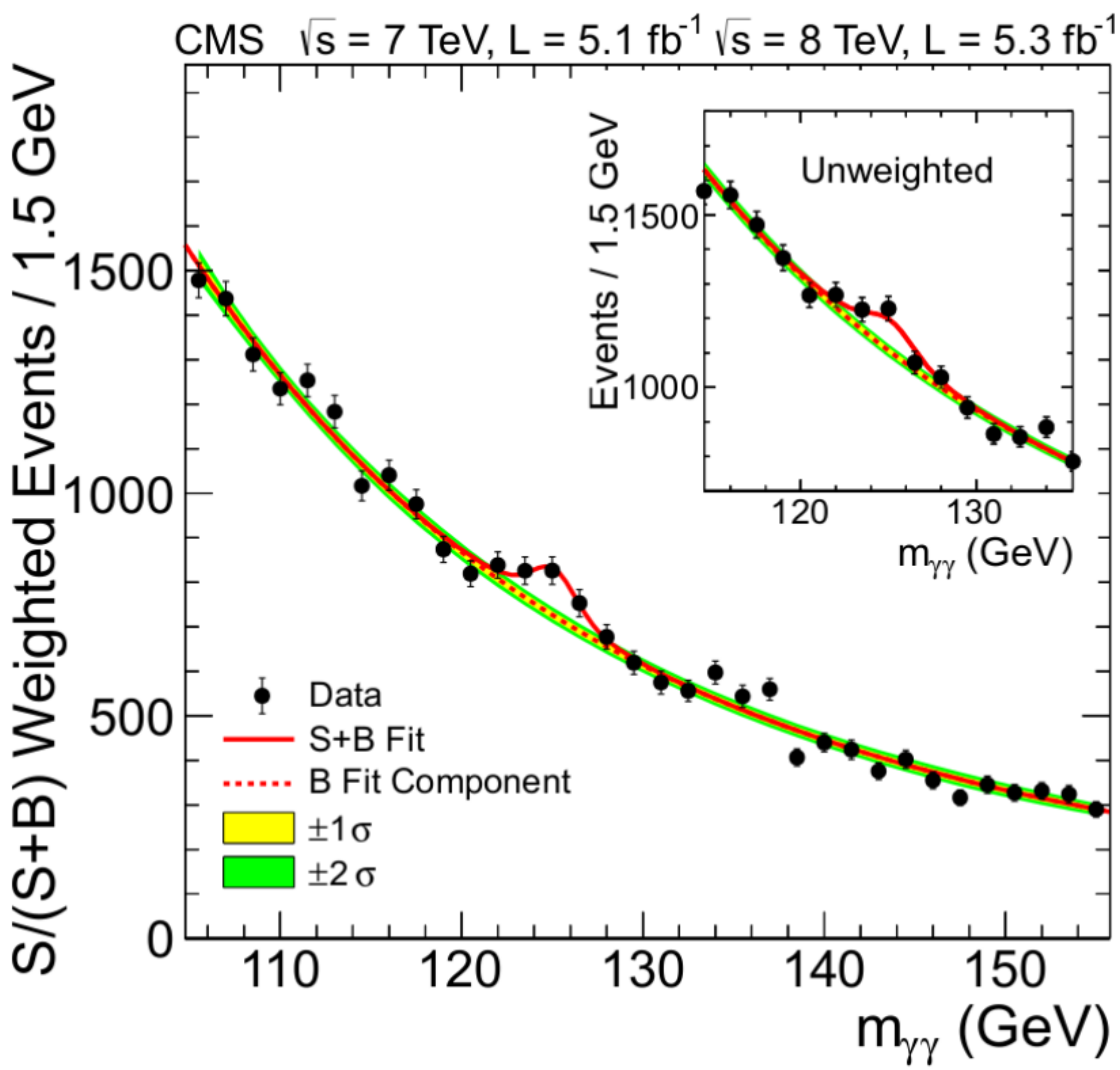
This is our Higgs cross-section

< 1 in a billion events are Higgs bosons!

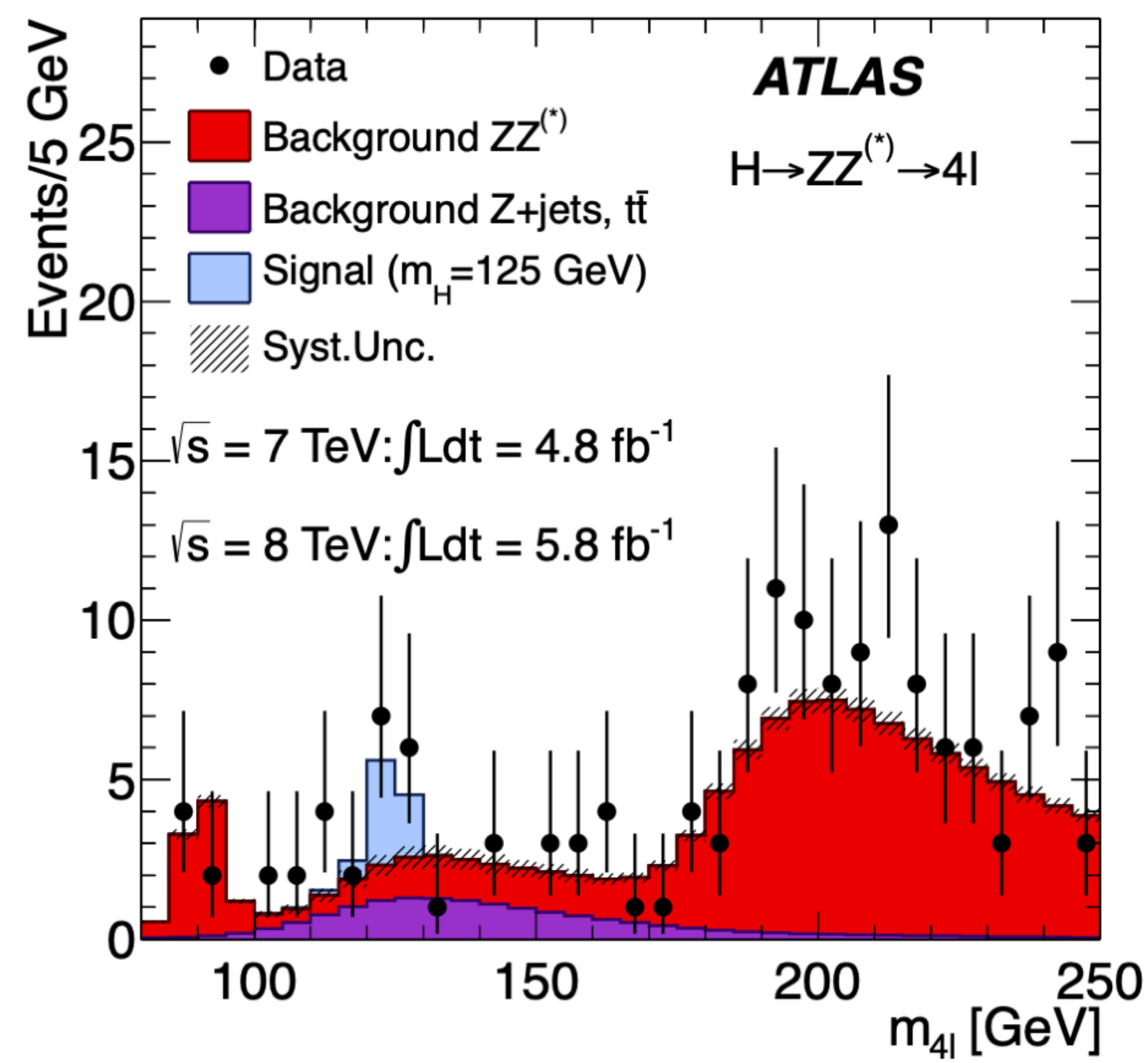


Discovery of the Higgs

- The Higgs was last fundamental particle to be discovered
  - discovered in 2012 by both CMS and ATLAS experiments
- Mass measured to be ~ 125 GeV



H→γγ



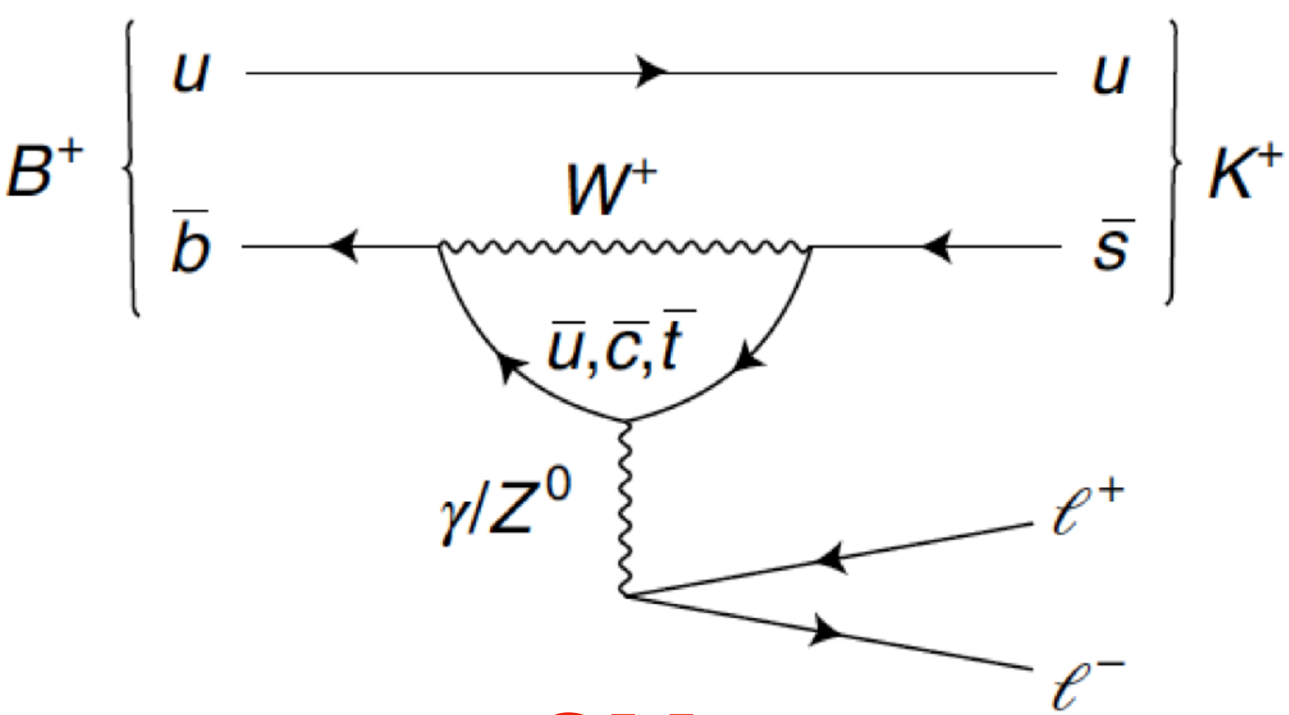
H→ZZ

What if we can’t produce new particle directly?

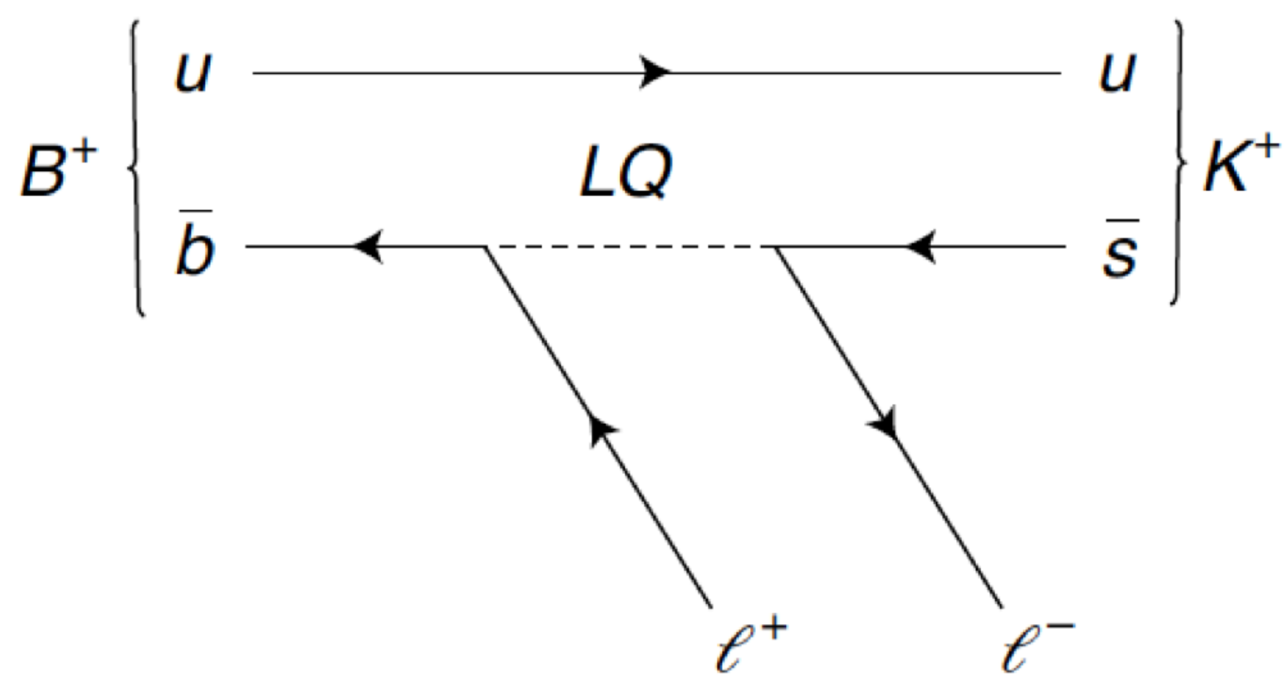
- If particles are too high energy we may not be able to produce them at our colliders

- But we can still influence physics processes → off-shell propagators in Feynman diagrams

- We can see influence in measurable processes such rare SM decays e.g B meson decays



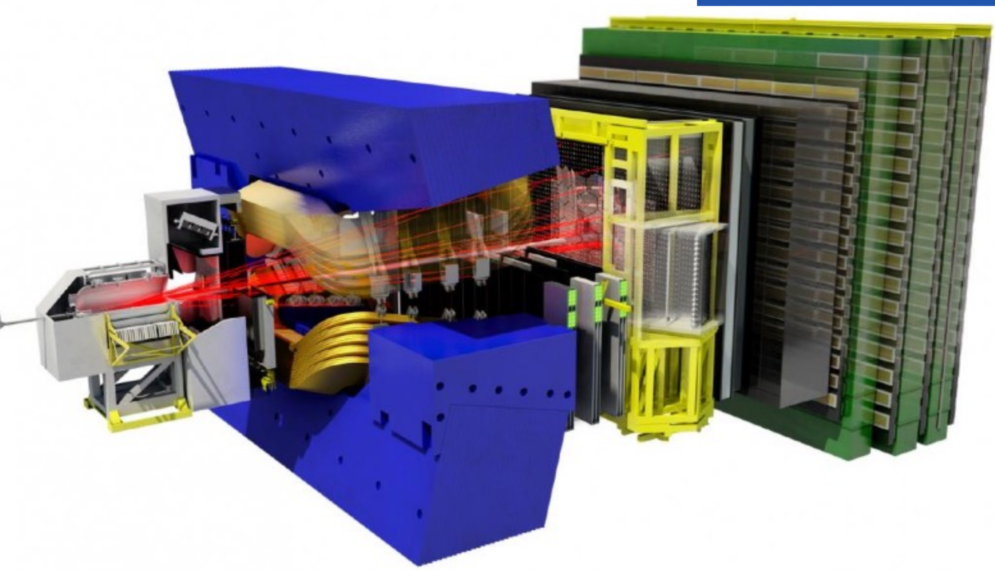
SM



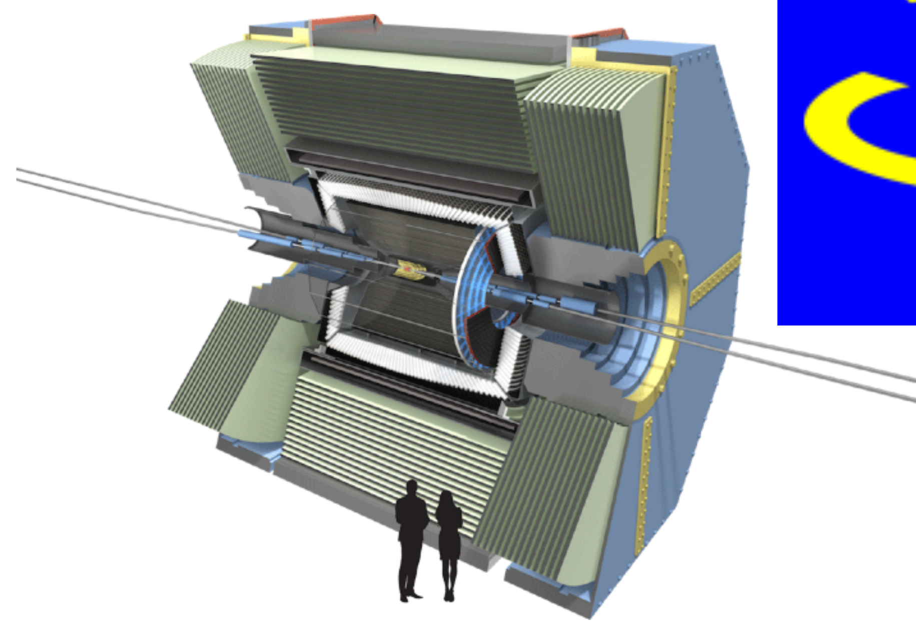
non-SM

B-physics experiments

Forward spectrometer built around LHC ring
Exploit large B production cross-sections in pp collisions



e^+e^- collider tuned to energy of Υ meson ($b\bar{b}$ meson) ~ 10 GeV



- Study properties of B mesons including rare decays and CP-violation in quark sector

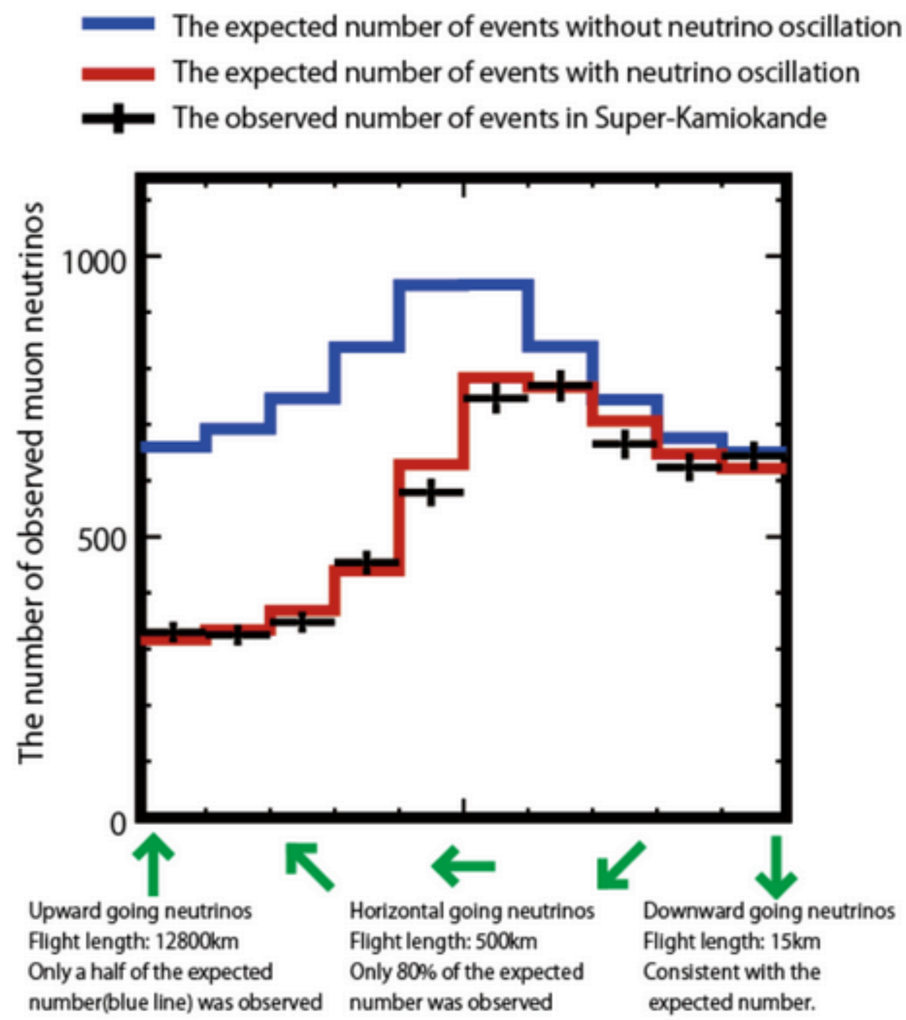
Neutrino experiments

- Neutrinos first proposed to explain energy spectrum of weak decays - originally thought to be massless

- Neutrino “oscillations” discovered in late 1990’s by Super-Kamiokande which solved mystery of “missing” solar neutrinos

- Neutrinos change type as they propagate

- The implication of this discovery is that neutrinos have mass



$$P_{\nu_\alpha \to \nu_\beta} \approx \sin^2(2\theta)\sin^2\left(1.27\frac{\Delta m^2[\mathrm{eV}^2]\cdot L[\mathrm{km}]}{E[\mathrm{GeV}]}\right)$$

PNMS matrix

- Oscillations arise from mixing between the flavour and mass eigenstates
  - Mass and flavour eigenstates not the same
  - Flavour eigenstates are superposition of mass eigenstates and vice versa
- Neutrino mixing governed by Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix

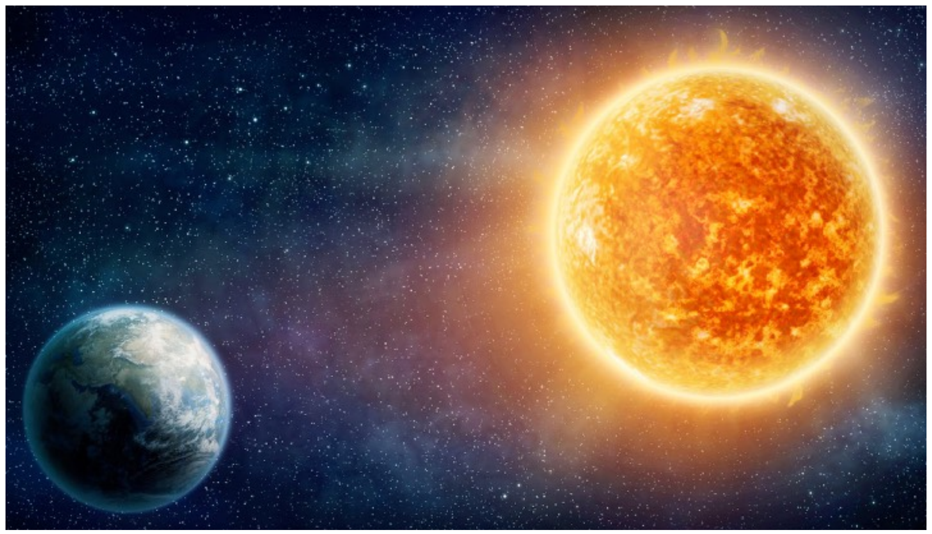
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{\text{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$U_{\text{PMNS}} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{CP}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{CP}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{CP}} & c_{23}c_{13} \end{pmatrix}$$

Space for CP-violation! - this has implications for explaining matter anti-matter asymmetry (no CP-violation = 0°, 180°)
Do anti-neutrinos oscillate differently compared to neutrinos?
Combination yields $232^{\circ}{}^{+39^{\circ}}_{-25^{\circ}}$ - some hint for CP-violation?

Neutrino experiments by baseline

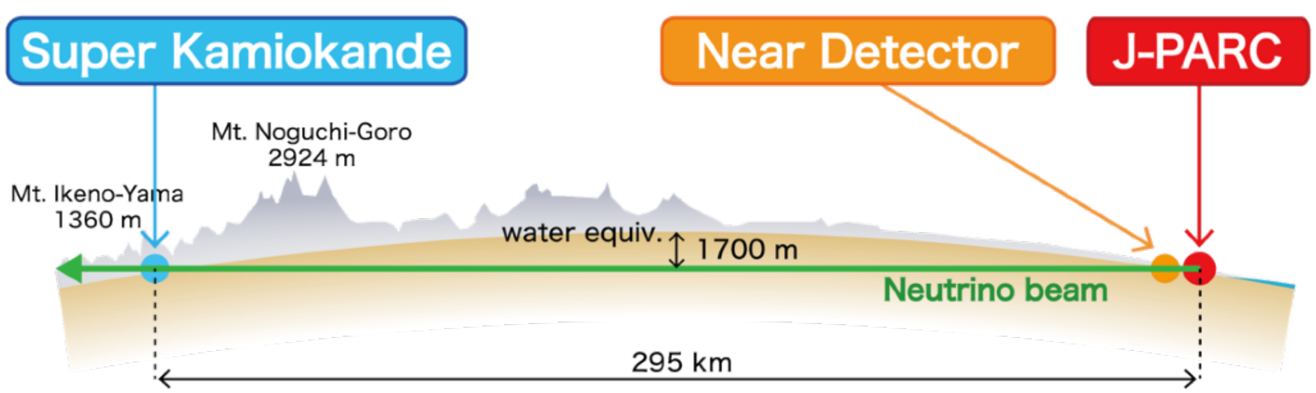
- Different "baseline" experiments (propagation distances) sensitive to different parameters



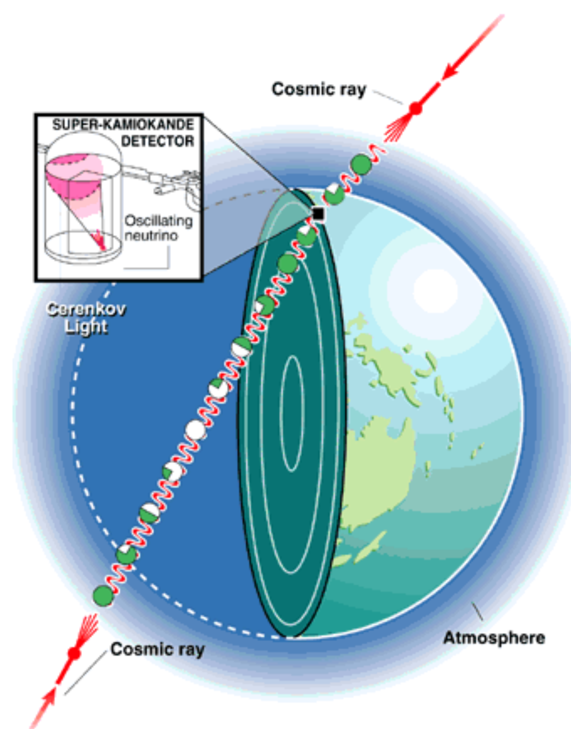
Solar: θ_{12}, Δm^2_{21}

Reactor: θ_{13}, Δm^2_{31}, θ_{12}, Δm^2_{21}

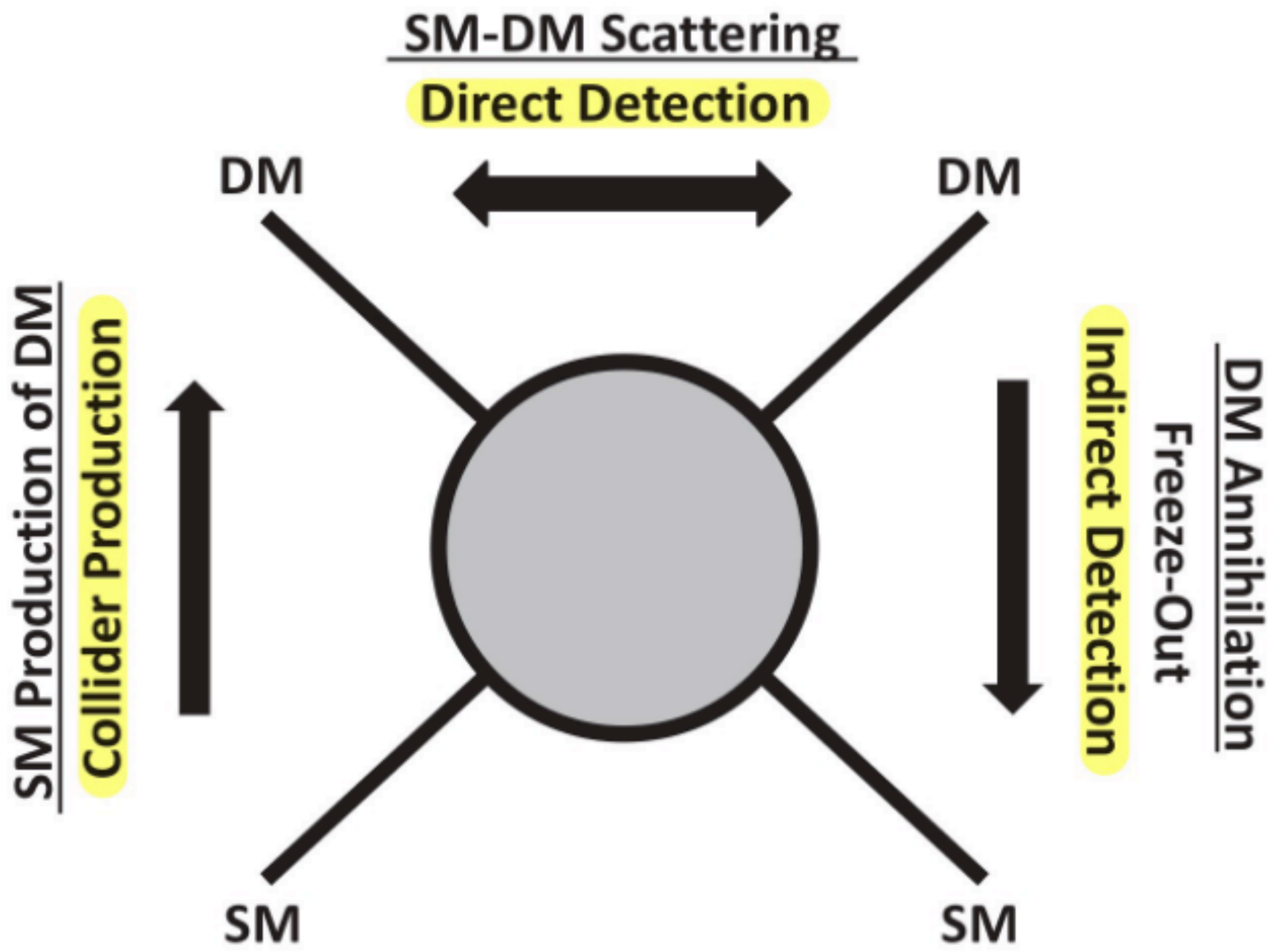
Accelerator: $\delta_{\rm CP}$, θ_{23}, Δm^2_{32}



Atmospheric: θ_{23}, Δm^2_{32}

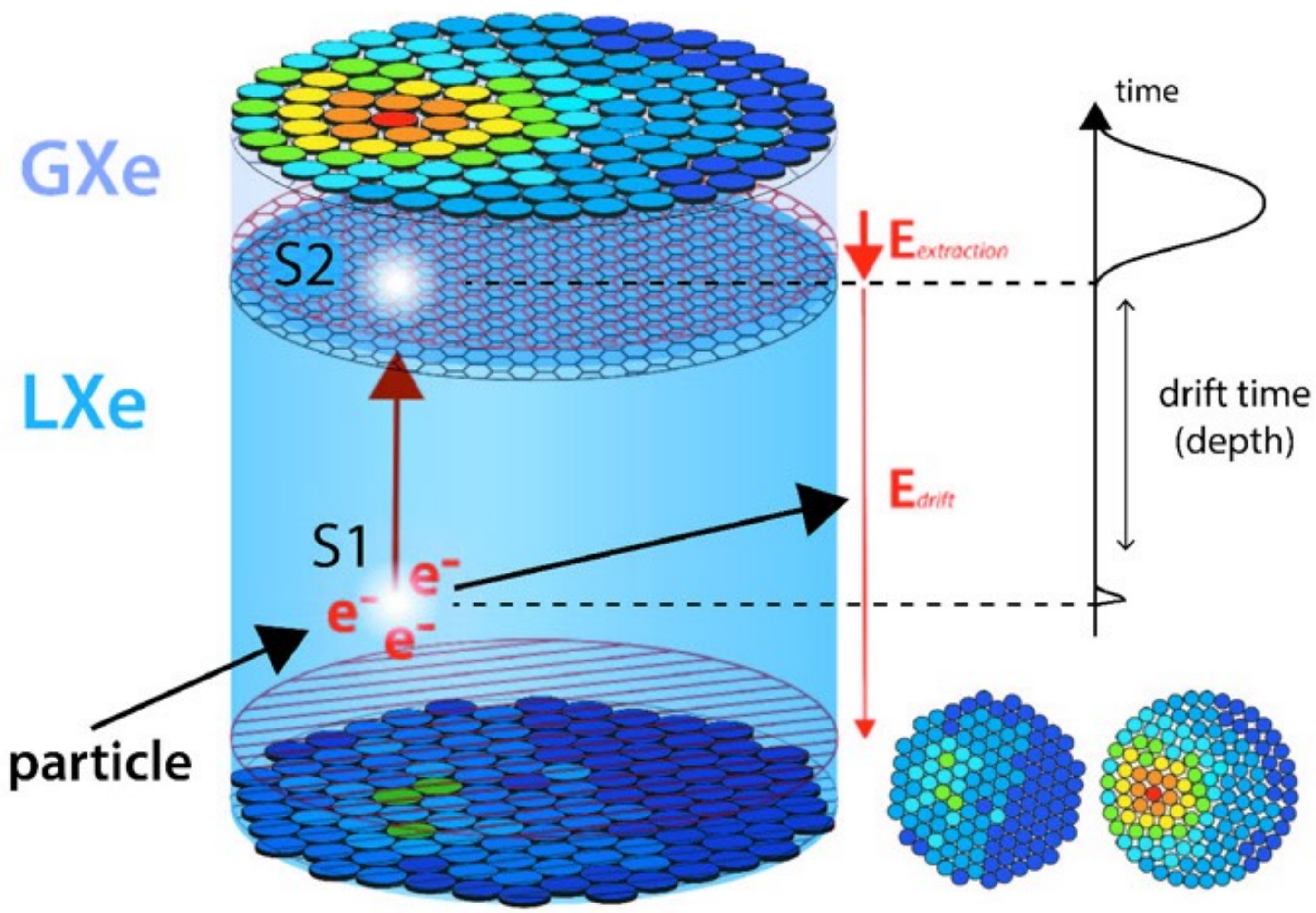


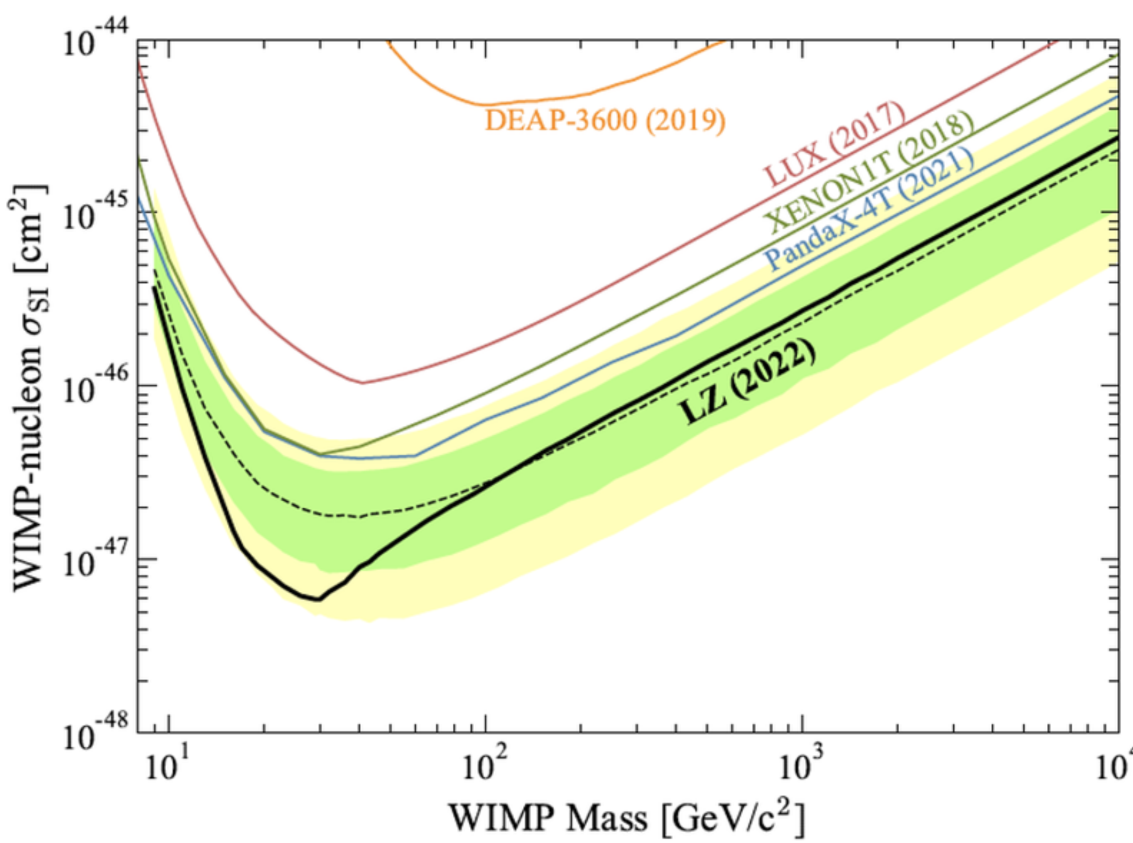
- Direct dark matter experiments search for SM scattering off target



- WIMP = Weakly Interacting Massive Particles

- Xenon experiments such as LZ, PandaX-4T, and XENON1T detect photon (S1) and electron (S2) originating from nuclear recoils from DM scattering





Summary

- The Standard Model of Particle Physics is our best description of the fundamental building blocks of the Universe to date

- But we know it has issues and leaves several observations about the universe unexplained

- The latest Particle Physics experiments are looking to understand these puzzles and by doing so we will learn about the origin and structure of the Universe

Backup

- Lagrangian is a function that described dynamics of a system
- Classically L = kinematic energy - potential
- In QFT Lagrangian density describes fields instead and encodes their interactions

$$\mathscr{L}_{\text{QED}} = \bar{\psi}(i\gamma^{\mu}D_{\mu} - m)\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

QED Lagrangian

$$\begin{gathered}
\mathcal{L}_{SM} = -\tfrac{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 - \tfrac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - 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)) - \tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \tfrac{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) - \tfrac{1}{2}\partial_\mu H \partial_\mu H - 2M^2\alpha_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \tfrac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \\
\beta_h\left(\tfrac{2M^2}{g^2} + \tfrac{2M}{g}H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)\right) + \tfrac{2M^4}{g^2}\alpha_h - \\
g\alpha_h M\left(H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-\right) - \\
\tfrac{1}{8}g^2\alpha_h\left(H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2\right) - \\
gMW^+_\mu W^-_\mu H - \tfrac{1}{2}g\tfrac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \\
\tfrac{1}{2}ig\left(W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)\right) + \\
\tfrac{1}{2}g\left(W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) + W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)\right) + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) + \\
M\left(\tfrac{1}{c_w}Z^0_\mu\partial_\mu\phi^0 + W^+_\mu\partial_\mu\phi^- + W^-_\mu\partial_\mu\phi^+\right) - ig\tfrac{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\tfrac{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^+) - \\
\tfrac{1}{4}g^2 W^+_\mu W^-_\mu\left(H^2 + (\phi^0)^2 + 2\phi^+\phi^-\right) - \tfrac{1}{8}g^2\tfrac{1}{c_w^2}Z^0_\mu Z^0_\mu\left(H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2\phi^+\phi^-\right) - \\
\tfrac{1}{2}g^2\tfrac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) - \tfrac{1}{2}ig^2\tfrac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + \\
W^-_\mu\phi^+) + \tfrac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c_w^2 - 1)Z^0_\mu A_\mu\phi^+\phi^- - \\
g^2 s_w^2 A_\mu A_\mu\phi^+\phi^- + \tfrac{1}{2}ig_s\lambda^a_{ij}(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu - \bar{e}^\lambda(\gamma\partial + m^\lambda_e)e^\lambda - \bar{\nu}^\lambda(\gamma\partial + m^\lambda_\nu)\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + \\
m^\lambda_u)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial + m^\lambda_d)d^\lambda_j + igs_w A_\mu\left(-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)\right) + \\
\tfrac{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{d}^\lambda_j\gamma^\mu(\tfrac{4}{3}s_w^2 - 1 - \gamma^5)d^\lambda_j) + \\
(\bar{u}^\lambda_j\gamma^\mu(1 - \tfrac{8}{3}s_w^2 + \gamma^5)u^\lambda_j)\} + \tfrac{ig}{2\sqrt{2}}W^+_\mu\left((\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)U^{lep}{}_{\lambda\kappa}e^\kappa) + (\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)\right) + \\
\tfrac{ig}{2\sqrt{2}}W^-_\mu\left((\bar{e}^\kappa U^{lep\dagger}{}_{\kappa\lambda}\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\kappa\lambda}\gamma^\mu(1+\gamma^5)u^\lambda_j)\right) + \\
\tfrac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_e(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1-\gamma^5)e^\kappa) + m^\lambda_\nu(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1+\gamma^5)e^\kappa)\right) + \\
\tfrac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_e(\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1+\gamma^5)\nu^\kappa) - m^\kappa_\nu(\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1-\gamma^5)\nu^\kappa)\right) - \tfrac{g}{2}\tfrac{m^\lambda_\nu}{M}H(\bar{\nu}^\lambda\nu^\lambda) - \\
\tfrac{g}{2}\tfrac{m^\lambda_e}{M}H(\bar{e}^\lambda e^\lambda) + \tfrac{ig}{2}\tfrac{m^\lambda_\nu}{M}\phi^0(\bar{\nu}^\lambda\gamma^5\nu^\lambda) - \tfrac{ig}{2}\tfrac{m^\lambda_e}{M}\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda) - \tfrac{1}{4}\bar{\nu}_\lambda M^R_{\lambda\kappa}(1-\gamma_5)\hat{\nu}_\kappa - \\
\tfrac{1}{4}\bar{\nu}_\lambda M^R_{\lambda\kappa}(1-\gamma_5)\hat{\nu}_\kappa + \tfrac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_d(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m^\lambda_u(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j)\right) + \\
\tfrac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_d(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m^\kappa_u(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j)\right) - \tfrac{g}{2}\tfrac{m^\lambda_u}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \\
\tfrac{g}{2}\tfrac{m^\lambda_d}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2}\tfrac{m^\lambda_u}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \tfrac{ig}{2}\tfrac{m^\lambda_d}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu\bar{G}^a G^b g^c_\mu + \\
\bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \tfrac{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^+ - \\
\partial_\mu\bar{X}^- X^-) - \tfrac{1}{2}gM\left(\bar{X}^+ X^+ H + \bar{X}^- X^- H + \tfrac{1}{c_w^2}\bar{X}^0 X^0 H\right) + \tfrac{1-2c_w^2}{2c_w}igM\left(\bar{X}^+ X^0\phi^+ - \bar{X}^- X^0\phi^-\right) + \\
\tfrac{1}{2c_w}igM\left(\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-\right) + igMs_w\left(\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-\right) + \\
\tfrac{1}{2}igM\left(\bar{X}^+ X^+\phi^0 - \bar{X}^- X^-\phi^0\right).
\end{gathered}$$

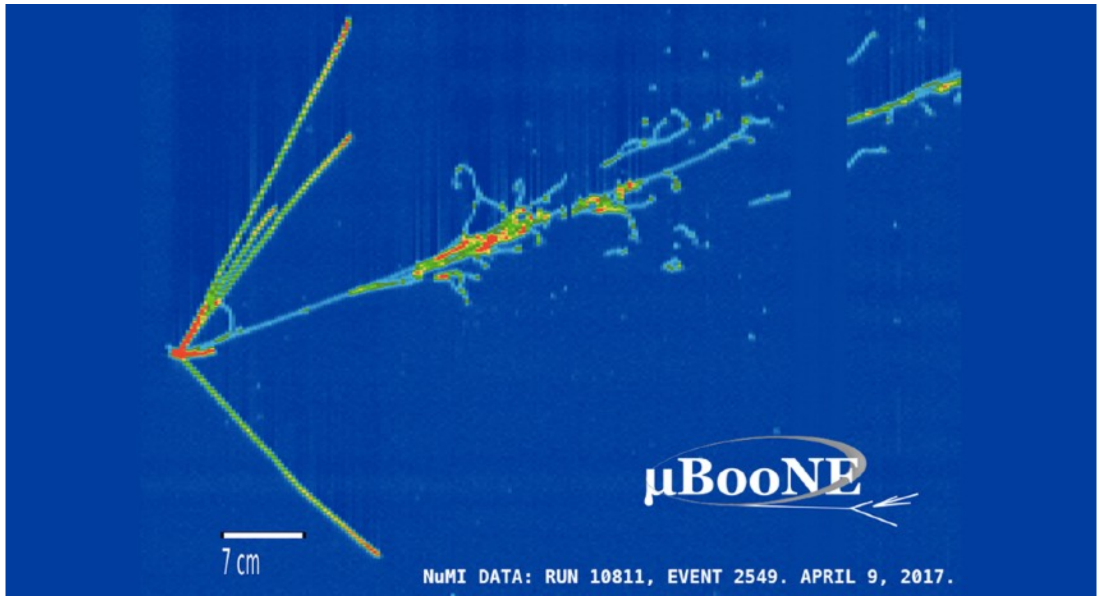
SM Lagrangian

Triggering

- To produce rare processes LHC collides ~ 50 protons at a time, 40 million times a second
  - An event requires ~ 1 MB for storage = 40 million MB per second
- No way to read out and store all of this data
- As we saw previously most events at pp colliders are uninteresting
- We use “trigger” to make very quick decision about whether an event should be stored or thrown away
- Trigger performs quick coarse event reconstruction and decides if event look interesting before storage

Neutrino detectors

- Water Cherenkov detectors (e.g Super-K, Hyper-K (in future))
  - Charged particles that travel faster than light in a medium which causes them to emit light “Cherenkov radiation”
  - This creates cone of light analogous to “sonic-boom”
- Liquid argon (MicroBooNE, DUNE (in future))
  - Neutrinos interact and produce charged particles which ionise the liquid argon



A brief history of particle colliders

- Accelerate particles to very high energy in two opposing beams
- Collide the beams and measure what comes out
- If energy if high enough we can produce new particles
- Precision measurements also tell us something!

1950s—1970s

Proton synchrotron
Circumference: 628m

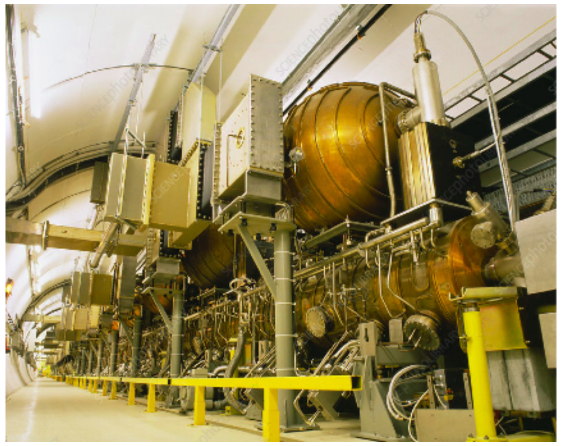
Indirect evidence for Z boson

~1980s

Super Proton synchrotron
Circumference: 7km

W and Z bosons

~1990s



LEP
Circumference: 27km

Precision measurements e.g 3 neutrino families

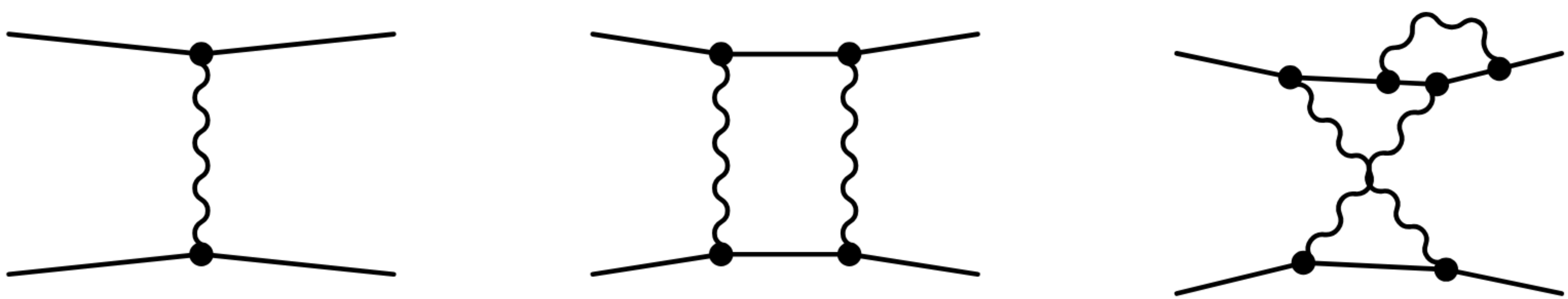
~1990s—2000s

Tevatron
Circumference: 6.3km

Top quark

Perturbation Theory

- Each diagram represents a term in the perturbation theory expansion of the amplitude
- A full calculation contains an infinite number of diagrams
- But each diagram involves larger power of coupling (g), so we only need to consider first few orders to get accurate prediction

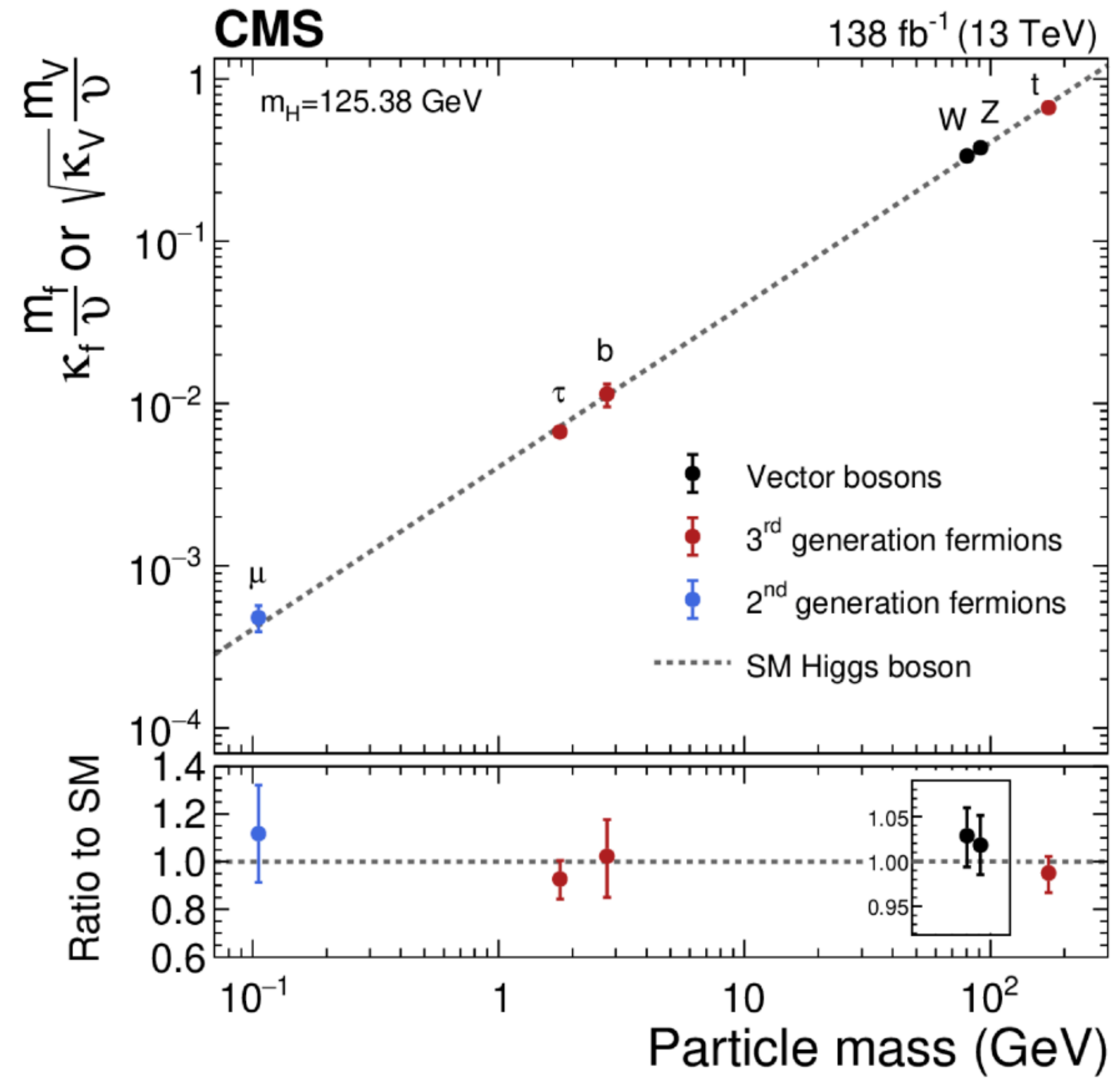


g^2 g^4 g^6

QED: g = e = $\sqrt{4\pi\alpha} \approx 0.3$

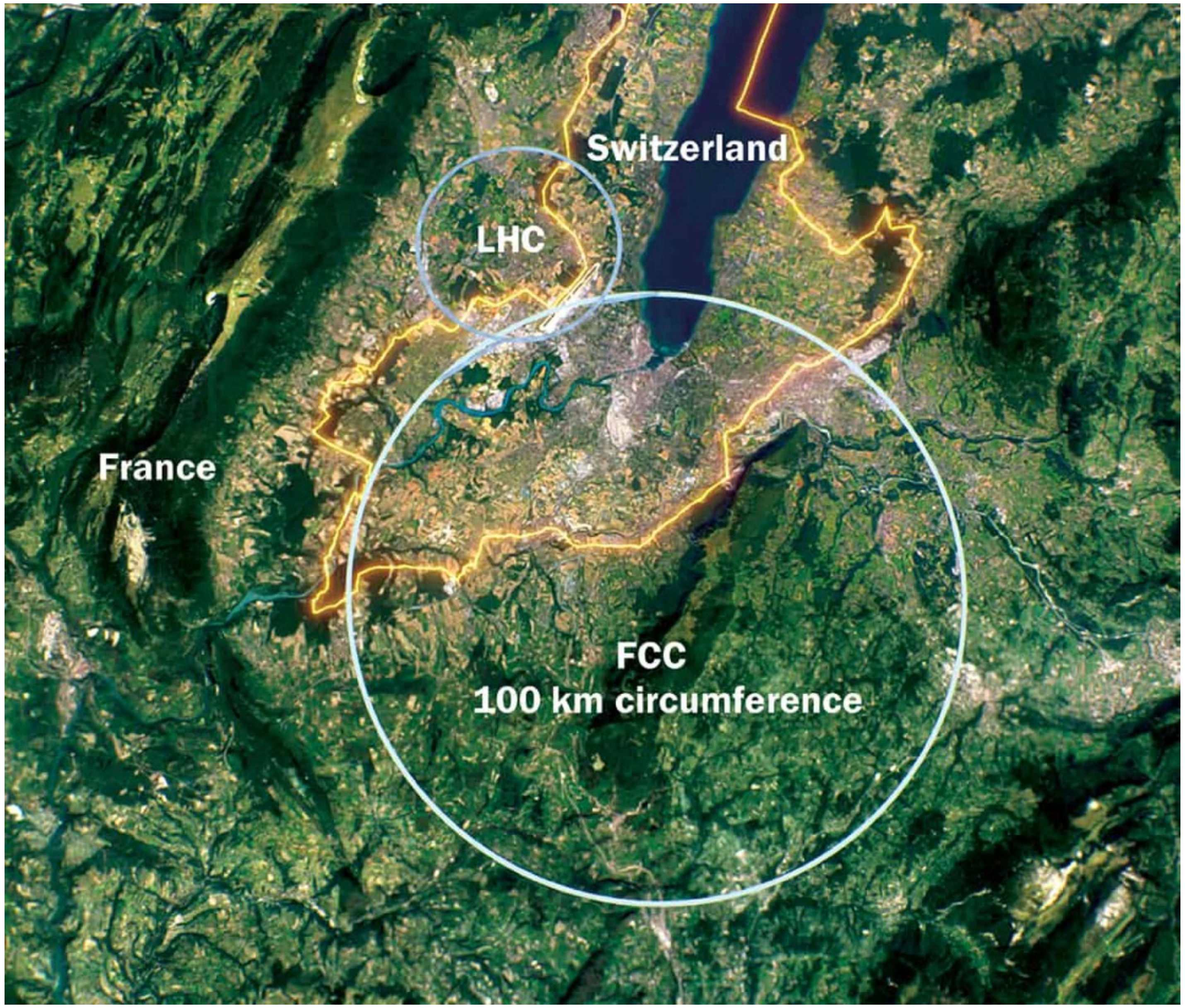
Does the Higgs behave as we expect?

- Observed Higgs decay in several final states
- Measured interaction strengths to many particles
- Measured properties such as spin (=0), and CP
- Everything looks as expected **within uncertainties**



The next frontier

- LHC to end in ~2040 (only 1/10 of data collected so far!)
- Preferred next machine would be 100 km collider at CERN
- Would begin in ~mid-2040 with 365 GeV e^+e^- collisions (compared to 210 GeV @ LEP)
- Followed by **100 TeV** proton-proton in ~ 2070 (compared to 14 TeV @ LHC)



How the Higgs field gives particles mass

- Particles with mass interact with the Higgs field and the strength of the interaction determines their mass