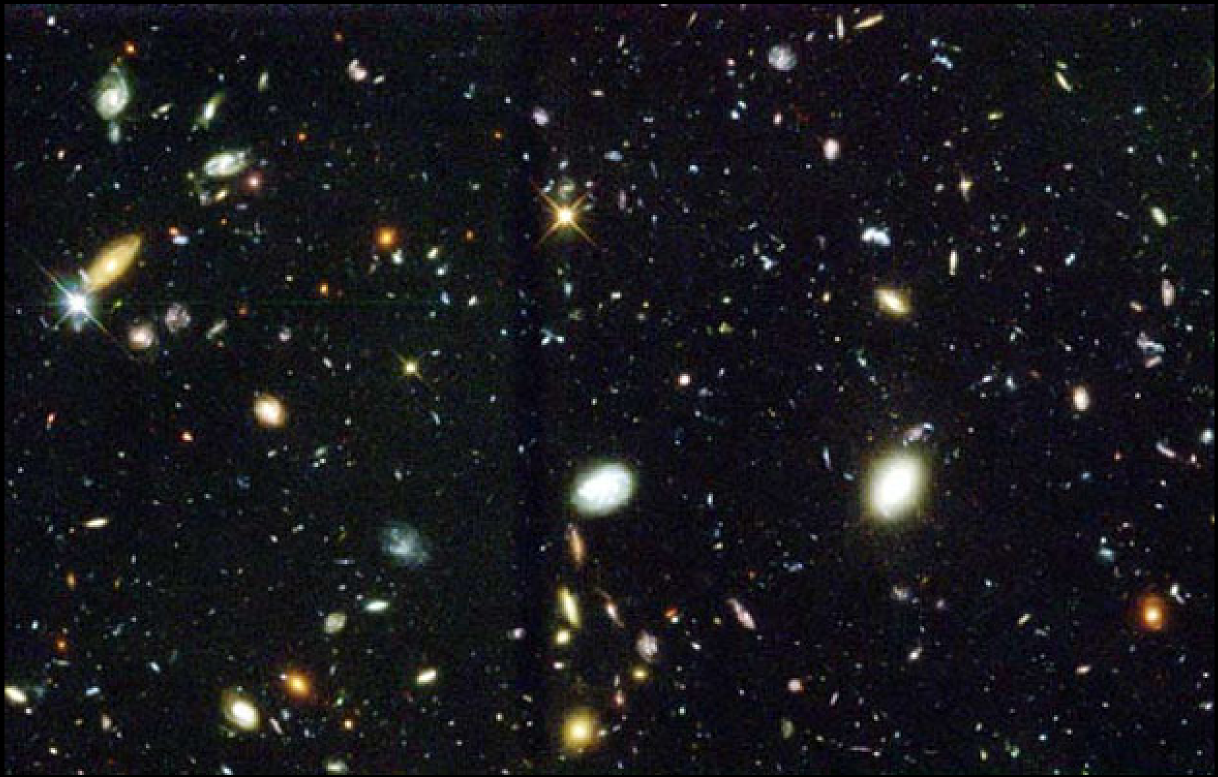
# The Future of Particle Cosmology (after LHC Run II)


Hooman Davoudiasl

HET Group, Brookhaven National Laboratory

NExT PhD Workshop 2017, Abingdon, UK

June 26-29, 2017

# Lecture 1: Preliminaries

- Four lectures to cover a vast subject

- To be treated, at best, as a survey of some key ideas

- The title: “The Future of ....”:

My inability to time-travel $\Rightarrow$ Have no real clue...!

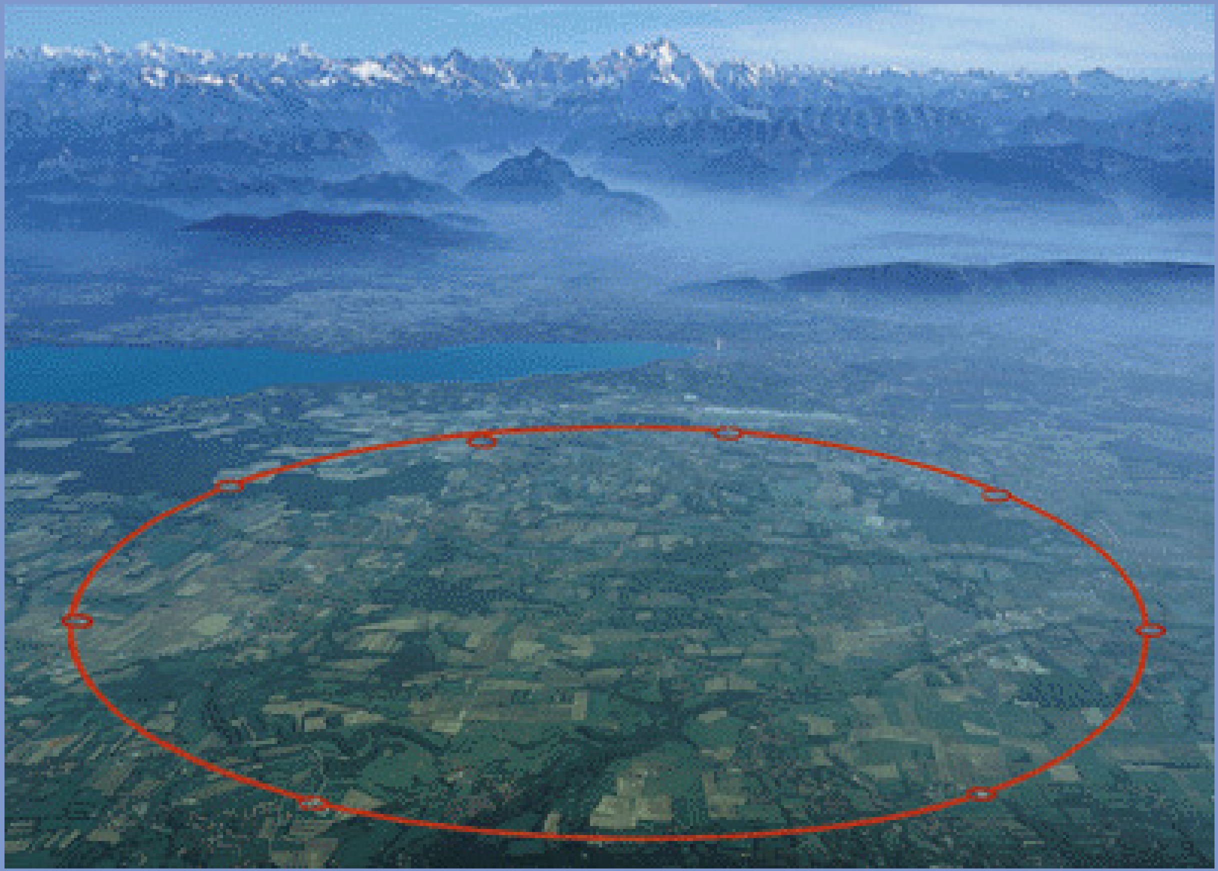
- Some educated guesses, but there is subjectivity involved

- How about the sub-title: (after LHC Run II)?

- Questions: What is the LHC? What is Run II?

## LHC: Large Hadron Collider ($pp$ collider) at CERN

CERN: Conseil Européen pour la Recherche Nucléaire



**Beam energy: $2 \times 7$ TeV (design)**

**Currently running at $2 \times 6.5$ TeV**

**Circumference (km): 26.659**

- LHC commissioned in 2009
- High energy particle physics: ATLAS and CMS experiments
- LHCb: $B$ mesons, *flavor*
- Other experiments: nuclear physics and low energy hadron physics
- Run I: 2010-2012 at center of mass energy $\sqrt{s} = 7, 8$ TeV
- Higgs discovery in 2012
- Run I: About 25 fb$^{-1}$ for ATLAS and CMS
- Run II: Since 2015, at $\sqrt{s} = 13$ TeV, until the end of 2018
- Run II: $\sim 100$ fb$^{-1}$ of data for ATLAS and CMS (so far $\sim 40$ fb$^{-1}$)
- Back in 2021, after some upgrades

⋆ *Before talking about the future of particle cosmology, let us briefly summarize the status of particle physics.*

• LHC: initially to look for completion of the **Standard Model** (SM) of particle physics

*What gives known fundamental particles their masses?*

• The discovery of the **Higgs** at about 125 GeV in 2012, and subsequent measurements, seem to have largely answered this question.

• So far, LHC data have mainly confirmed the SM

• Some statistically interesting, but *inconclusive*, evidence for deviations

• For example, some discrepancies in flavor physics ($\sim 3\sigma$)

• Data from other particle physics experiments, in particular the muon anomalous magnetic moment $g_\mu - 2$ ($\sim 3.5\sigma$)

• **What is the SM?**

# SM: The most precise description of non-gravitational* microscopic physics

* *General Relativity is the current state-of-the-art theory of gravity*

## Ingredients of the SM:

- Gauge group: $SU(3)_c \times SU(2)_L \times U(1)_Y$ (spin-1 gauge fields)

- $SU(2)_L \times U(1)_Y$ spontaneously broken by the Higgs scalar (spin-0) to $U(1)_{EM}$

- Fermions (spin 1/2): three *generations* of quarks and leptons
- Chiral representation under $SU(2)_L$, only left-handed doublets
- Parity broken by $SU(2)_L$ interactions

- Quarks: charged under $SU(3)_c$ color   Quantum Chromodynamics (QCD)

- Leptons: uncharged under $SU(3)_c$

- $SU(3)_c \times SU(2)_L \times U(1)_Y$ assignments

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix} \sim (\mathbf{3}, \mathbf{2}, \tfrac{1}{6}) \quad ; \quad u_R \sim (\mathbf{3}, \mathbf{1}, \tfrac{2}{3}) \quad ; \quad d_R \sim (\mathbf{3}, \mathbf{1}, -\tfrac{1}{3})$$

$$\begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix} \sim (\mathbf{1}, \mathbf{2}, -\tfrac{1}{2}) \quad ; \quad \nu_{eR} \notin \text{SM} \quad ; \quad e_R \sim (\mathbf{1}, \mathbf{1}, -\mathbf{1})$$

- Three generations with identical gauge quantum numbers

Quarks: $\begin{pmatrix} u \\ d \end{pmatrix} \quad ; \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad ; \quad \begin{pmatrix} t \\ b \end{pmatrix}$ with EM charges $\begin{pmatrix} +2/3 \\ -1/3 \end{pmatrix}$

Leptons: $\begin{pmatrix} \nu_e \\ e \end{pmatrix} \quad ; \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \quad ; \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$ with EM charges $\begin{pmatrix} 0 \\ -1 \end{pmatrix}$

- One scalar Higgs doublet: $H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix} \sim (\mathbf{1}, \mathbf{2}, \tfrac{1}{2})$

$Q = T_3 + Y \quad ; \quad T_3 = \begin{pmatrix} +1/2 \\ -1/2 \end{pmatrix}$ ($3^{rd}$ component of isospin)

- The SM Lagrangian has several sectors: kinetic terms for gauge fields, fermions, and the Higgs, as wells as Yukawa couplings between the Higgs and fermions, plus the Higgs potential.

- Masses from couplings to the Higgs vacuum expectation value (vev)

- $\langle H \rangle = \begin{pmatrix} 0 \\ v_H/\sqrt{2} \end{pmatrix}$ with $v_H \approx 246$ GeV

- Higgs potential: $V(H) = -\mu^2 H^\dagger H + \lambda_H (H^\dagger H)^2$

- Higgs kinetic term: $(D_\mu H)^\dagger D_\mu H$ with $D_\mu \equiv \partial_\mu + i\frac{g_1}{2} B_\mu + i g_2 \vec{\tau}.\vec{W}_\mu$

$\langle H \rangle \neq 0 \Rightarrow M_W = \frac{g_2}{2} v_H \approx 80.4$ GeV ; $M_Z = \frac{1}{2}\sqrt{g_1^2 + g_2^2}\, v_H \approx 91.2$ GeV

- $U(1)_{EM}$ preserved at low energies: $M_\gamma = 0$

- Yukawa couplings:

$$\boxed{-\mathcal{L}_Y = Y^u_{ij}\,\tilde{H}\,\bar{q}^i_L\,u^j_R + Y^d_{ij}\,H\,\bar{q}^i_L\,d^j_R + Y^e_{ij}\,H\,\bar{\ell}^i_L\,e^j_R}$$

- $\tilde{H} = i\tau_2 H^*$ ; $i, j = 1, 2, 3$

- $\mathcal{L}_Y \to$ Three $3 \times 3$ mass matrices: $\mathbf{m_u}, \mathbf{m_d}, \mathbf{m_e}$ with $\boxed{\mathbf{m_f} = \mathbf{Y_f}\,\frac{v_H}{\sqrt{2}}}$

- Diagonalize $\mathbf{m_f}$ with $\mathbf{U_L}$ and $\mathbf{U_R}$ unitary matrices: $f_i \to U_{ij} f_j$

- Charged current ($W^\pm$): $\bar{u}^i_L \gamma_\mu d^i_L \to \bar{u}^i_L \gamma_\mu \mathbf{V_{ij}} d^j_L$, where $\mathbf{V} \equiv \mathbf{U_L^{u\dagger} U_L^d}$

- $\mathbf{V}$ is the unitary Cabibbo-Kobayashi-Maskawa (CKM) matrix

- CKM, 4 parameters: 3 mixing angles and one phase $\delta$

$N$ generations: $2N^2$ (real parameters) $-N^2$ (conditions) $-(2N-1)$ (quark rephasings) $= (N-1)^2$

- $m_e, m_\mu, \ldots, m_t$; with $m_e = 0.511$ MeV and $m_t = 173.2$ GeV

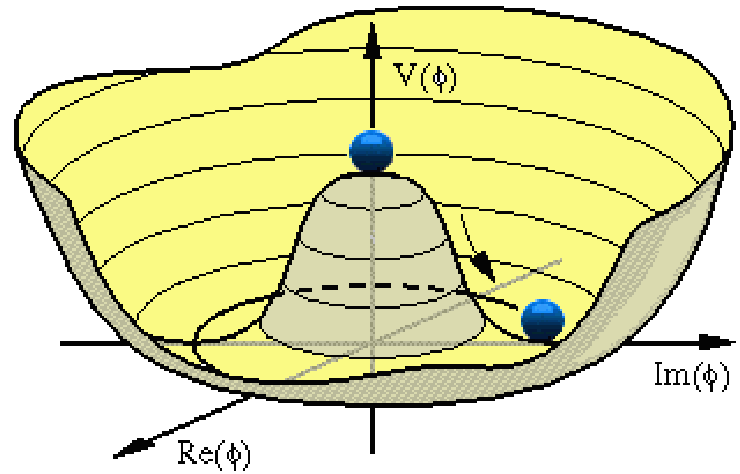
Wide range of fermion masses; flavor puzzle

- In minimal SM, no right-handed neutrinos: $m_\nu = 0$
- Not good! In conflict with a large body of solid neutrino oscillation data.

## Electroweak symmetry breaking (EWSB) in the SM

- $V(H) = -\mu^2 H^\dagger H + \lambda_H (H^\dagger H)^2$

$M_H = \sqrt{2\,\lambda}\, v_H$




- $M_H \approx$ 125 GeV $\Rightarrow \lambda \approx 0.13$

- Thermal loops: cubic term in $V(T)$

- Cubic term $\rightarrow$ barrier between the symmetric and broken phase; degenerate minima at $T = T_c$; transition by tunneling

- Strong first order phase transition: $v_H(T_c)/T_c \gtrsim 1$; departure from thermal equilibrium

- In the SM: $\dfrac{v_H(T_c)}{T_c} \approx \dfrac{2M_W^3 + M_Z^3}{2\pi\lambda v_H^3} \approx 0.15$   Quite weak!

$v_H(T_c)/T_c \gtrsim 1$ would require $M_H \lesssim 50$ GeV

# CP Violation in SM

- Originates from a single phase $\delta$ in the CKM matrix

$$\mathbf{V} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_2 & -s_2 \\ 0 & s_2 & c_2 \end{pmatrix} \begin{pmatrix} c_1 & -s_1 & 0 \\ s_1 & c_1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -e^{i\delta} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_3 & s_3 \\ 0 & -s_3 & c_3 \end{pmatrix}$$

$s_i = \sin\theta_i$, $c_i = \cos\theta_i$

- Rephasing invariant: $J = s_1^2 s_2 s_3 c_1 c_2 c_3 \sin\delta \approx 3 \times 10^{-5}$

Jarlskog, 1985

- One can show CP conserved if $m_i^{u(d)} = m_j^{u(d)}$, for $i \neq j$

$$\Rightarrow \text{CP violation in SM} \propto J \prod_{i \neq j} (m_i^u - m_j^u)(m_i^d - m_j^d)$$

- *Intrinsic CP violation in SM quite small even though $\delta \sim 1$.*

# Some Symmetries of the SM

• Baryon ($B$) and lepton ($L$) numbers are *accidental symmetries* of the SM Lagrangian, *i.e.* consequences of gauge invariance and renormalizability. They can be violated by higher dimension operators which can be suppressed by very large mass scales.

• Parity $[SU(2)_L]$ and CP (CKM phase) not respected, but CPT is.

• Electroweak quantum processes, through triangle anomalies, violate $B+L$. At $T=0$ this occurs through extremely suppressed tunneling between vacua. At $T \gtrsim 100$ Gev this can happen by going over the barrier separating vacua, via *sphaleron* processes, at non-negligible rate.

• $B-L$ is preserved at both the classical and quantum level by the interactions of the SM.

# SM: An Incomplete Description of Nature!

• A wealth of data from neutrino flavor oscillation experiments (see the Neutrino Lectures) strongly imply that neutrinos have masses $\lesssim 0.1$ eV. This requires adding new physics (*e.g.*, right-handed neutrinos) to the SM.

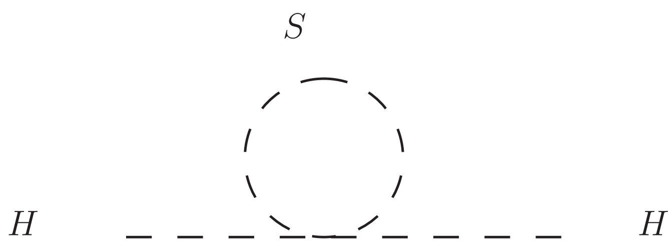
• Data from cosmology robustly point to the conclusion that $\sim 27\%$ of the cosmic energy budget is in the form of a substance that does not have significant interactions with ordinary matter. SM neutrinos are too light to be good candidates. There is no other particle in the SM that is cosmologically stable and feebly-coupled.

• Observations strongly favor a primordial cosmic baryon asymmetry at the $\sim 10^{-10}$ level. The SM cannot accommodate this asymmetry. Remarkably, this could be related to neutrino masses.

• A robust explanation of the isotropy and homogeneity of the Universe on large scales is provided by a period of exponential expansion, *i.e. inflation*, which the SM does not appear to provide. This type of physics is typically from very high scales and may not be a good target for LHC or other laboratory experiments. See, however, Bezrukov, Magnin, Shaposhnikov, 2008; Bezrukov, Rubio, Shaposhnikov, 2014

# Conceptual Hints for Extending SM

• *The Hierarchy Problem*: Why is $M_H$ stable against quantum corrections from large mass scales? For example, for $\lambda S^2 H^\dagger H$ ($M_S \gg m_H$):




$$\rightarrow \delta m_H^2 \sim \lambda/(16\pi^2)\, M_S^2$$

• If $M_S \sim M_{\text{Planck}} \approx 1.2 \times 10^{19}$ GeV, why $\frac{M_H^2}{M_{\text{Planck}}^2} \sim 10^{-34}$? (Why is gravity so weak?)

• The Higgs composite or new symmetries (supersymmetry) not far above $M_H$?

More severe version: Vacuum energy, the cosmological constant, $\Lambda^4 \lesssim 10^{-120} M_{\text{Planck}}$!

• $\theta\, G_{\mu\nu}\tilde{G}^{\mu\nu}$ allowed (CP-violating) in the QCD Lagrangian, yet neutron EDM measurements suggest $\theta \lesssim 10^{-9}$. Why is this parameter so small, given that CP is not a good symmetry of the SM?

• How do you make sense of gravity quantum mechanically? Maybe string theory is the answer. The resolution could be well beyond the reach of experiments.

# Agenda

• Over the remaining lectures we will address the "observational" shortcomings of the SM.

• We will focus on the baryon asymmetry of the Universe and DM.

• Motivation for solutions may be provided by models that also address the conceptual problems of the SM.

• Some of the ideas can be probed at the LHC, but there is a broad range of possibilities and other search avenues are also required.