The Higgs field and the early universe

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Outline

1. Standard Model and the reality of the Universe
   - Standard Model is in great shape!
   - All new physics at low scale—νMSM
   - Top-quark and Higgs-boson masses and vacuum stability

2. Stable Electroweak vacuum

3. Metastable vacuum and Cosmology
   - Safety today
   - Safety at inflation
Lesson from LHC so far – Standard Model is good

- SM works in all laboratory/collider experiments (electroweak, strong)
- LHC 2012 – final piece of the model discovered – Higgs boson
  - Mass measured $\sim 125$ GeV – weak coupling! Perturbative and predictive for high energies

- Add gravity
  - get cosmology
  - get Planck scale $M_P \sim 1.22 \times 10^{19}$ GeV as the highest energy to worry about
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Many things in cosmology are not explained by SM

### Experimental observations
- Dark Matter
- Baryon asymmetry of the Universe
- Inflation (nearly scale invariant spectrum of initial density perturbations)

### Laboratory also asks for SM extensions
- Neutrino oscillations
Nothing really points to a definite scale above EW

- Neutrino masses and oscillations (absent in SM)
  - Right handed neutrino between $1\text{ eV}$ and $10^{15}\text{ GeV}$

- Dark Matter (absent in SM)
  - Models exist from $10^{-5}\text{ eV}$ (axions) up to $10^{20}\text{ GeV}$ (Wimpzillas, Q-balls)

- Baryogenesys (absent in SM)
  - Leptogenesys scenarios exist from $M \sim 10\text{ MeV}$ up to $10^{15}\text{ GeV}$
Possible: New physics only at low scales – νMSM

Role of sterile neutrinos

$N_1 \quad M_1 \sim 1 - 50 \text{keV}: \text{(Warm) Dark Matter,}
\text{Note: } M_1 = 7 \text{keV has been seen in X-rays?!}

$N_{2,3} \quad M_{2,3} \sim \text{several GeV:}
\text{Gives masses for active neutrinos, Baryogenesys}

Asaka, Shaposhnikov’05; Asaka, Blanchet, Shaposhnikov’05
What happens at the scales between Electroweak 200 GeV and Planck $10^{19}$ GeV?

- Is SM consistent everywhere there?
- Does any problems appear?
- If yes, does it point to any scale?
Assuming SM (νMSM), the only “subtleties” left are the Higgs boson potential and inflation

### Higgs potential stability
- **Absolutely stable** Electroweak vacuum
- **Metastable** EW vacuum (true vacuum at/above Planck scale)

### Higgs and inflation
- Higgs boson *completely unrelated* to inflation
- Higgs boson “feels” inflation
  - interacts with inflaton field (e.g. changes mass depending in inflaton background)
  - non-minimal coupling with gravitational background (changes properties in curved background)
- Higgs boson *drives* inflation itself (Higgs inflation from non-minimal coupling to gravity)
Standard Model self-consistency and Radiative Corrections

- Higgs self coupling constant $\lambda$ changes with energy due to radiative corrections.

$$\begin{align*}
(4\pi)^2 \beta_\lambda &= 24\lambda^2 - 6y_t^4 \\
&\quad + \frac{3}{8} (2g_2^4 + (g_2^2 + g_1^2)^2) \\
&\quad + (-9g_2^2 - 3g_1^2 + 12y_t^2)\lambda
\end{align*}$$

- Behaviour is determined by the masses of the Higgs boson $m_H = \sqrt{2\lambda}v$ and other heavy particles (top quark $m_t = y_tv/\sqrt{2}$)

- If Higgs is heavy $M_H > 170$ GeV – the model enters *strong coupling* at some low energy scale – new physics required.
Lower Higgs masses: RG corrections push Higgs coupling to negative values

- For Higgs masses $M_H < M_{\text{critical}}$ coupling constant is negative above some scale $\mu_0$.
- The Higgs potential may become negative!
  - Our world is not in the lowest energy state!
  - Problems at some scale $\mu_0 > 10^{10}$ GeV?

Higgs potential $V(\phi) \simeq \lambda(\phi) \frac{\phi^4}{4}$
LHC result: SM is definitely perturbative up to Planck scale, and probably has metastable SM vacuum

Experimental values for $y_t$

$$M_t=172.38\pm0.66 \text{ GeV}, \quad M_h=125.02\pm0.31 \text{ GeV}$$

We live close to the metastability boundary – but on which side?!

Future measurements of top Yukawa and Higgs mass are essential!
March 2014 – metastable?

$M_t = 173.34 \pm 0.76$ GeV
July 2014 – oh, very metastable!

Mass of the Top Quark

(* preliminary)

CDF-I dilepton
CDF-II dilepton *
DØ-II dilepton
CDF-I lepton+jets
DØ-I lepton+jets
CDF-II lepton+jets
DØ-II lepton+jets
CDF-I alljets
CDF-II alljets *
CDF-II track
CDF-II MET+Jets
Tevatron combination *

\(M_T = 174.34 \pm 0.64\) GeV

\(\chi^2/\text{dof} = 10.8/11\) (46%)
September 2014 – hmm, maybe stable is ok?

$M_t = 172.38 \pm 0.66 \text{ GeV}$

CMS 2010, dilepton
JHEP 07 (2011) 049, 36 pb$^{-1}$
CMS 2010, lepton+jets
PAS TOP-10-009, 36 pb$^{-1}$
CMS 2011, dilepton
EPJC 72 (2012) 2202, 5.0 fb$^{-1}$
CMS 2011, lepton+jets
JHEP 12 (2012) 105, 5.0 fb$^{-1}$
CMS 2011, all-hadronic
EPJ C74 (2014) 2758, 3.5 fb$^{-1}$
CMS 2012, lepton+jets
PAS TOP-14-001, 19.7 fb$^{-1}$
CMS 2012, all-hadronic
PAS TOP-14-002, 18.2 fb$^{-1}$
CMS 2012, dilepton
PAS TOP-14-010, 19.7 fb$^{-1}$

CMS combination
September 2014

Tevatron combination
July 2014 arXiv:1407.2682
World combination March 2014
ATLAS, CDF, CMS, D0
**Determination of top quark Yukawa**

- Hard to determine mass in the events
- Hard to relate the “pole” (the same for “Mont-Carlo”) mass to the MS top quark Yukawa
  - NLO event generators
  - Electroweak corrections – important at the current precision goals!

- Build a lepton collider?
- Improve analysis on a hadron collider?
Higgs boson mass

**ATLAS and CMS**

**LHC Run 1**

<table>
<thead>
<tr>
<th>$m_H$ [GeV]</th>
<th>4σ signal strength ($\mu$)</th>
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<tbody>
<tr>
<td>124</td>
<td>0.5</td>
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<tr>
<td>124.5</td>
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<td>125</td>
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**CMS** $H \rightarrow \gamma \gamma$

**ATLAS** $H \rightarrow ZZ \rightarrow 4l$

**CMS** $H \rightarrow ZZ \rightarrow 4l$

All combined

Best fit

68% CL
Experiment (measurements of SM masses) – We are somewhere close to the boundary between stability and metastability

Stable Electroweak vacuum – looks safe

Metastable – is it ok?
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Stable EW vacuum – mostly anything works

- No problems throughout the whole thermal evolution of the Universe.
- Adding inflation – many examples
  - $R^2$ inflation
  - Separate scalar inflaton interacting with the Higgs boson
  - non-minimally coupled Higgs inflation

![Diagram showing the relationship between $n_s$, $r$, and $\xi$, with various inflation models and constraints.](image)
Higgs inflation at tree level

Scalar part of the (Jordan frame) action

\[ S_J = \int d^4x \sqrt{-g} \left\{ -\frac{M_P^2}{2} R - \frac{\xi}{2} h^2 R + g_{\mu\nu} \frac{\partial^\mu h \partial^\nu h}{2} - \frac{\lambda}{4} (h^2 - v^2)^2 \right\} \]

- \( h \) is the Higgs field; \( M_P \equiv \frac{1}{\sqrt{8\pi G_N}} = 2.4 \times 10^{18} \text{GeV} \)
- SM higgs vev \( v \ll \frac{M_P}{\sqrt{\xi}} \) – can be neglected in the early Universe
- At \( h \gg \frac{M_P}{\sqrt{\xi}} \) all masses are proportional to \( h \) – scale invariant spectrum!
Higgs inflation at tree level

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To get observed \( \delta T/T \sim 10^{-5} \)

\[ \frac{\sqrt{\lambda}}{\xi} = \frac{1}{49000} \]

Mathematical trick – conformal transformation

\[ g_{\mu\nu} \rightarrow \hat{g}_{\mu\nu} = \sqrt{1 + \frac{\xi \phi^2}{M_P^2}} g_{\mu\nu}, \]

leads to flattened potential: \( V(\phi) \rightarrow \hat{V}(\chi) = \frac{\lambda M_P^4}{4 \xi^2} \left(1 - e^{-\frac{2\chi}{\sqrt{6}M_P}}\right)^2 \)
CMB parameters are predicted

For large $\xi$ Higgs inflation

- spectral index: $n \simeq 1 - \frac{8(4N+9)}{(4N+3)^2} \simeq 0.97$
- tensor/scalar ratio: $r \simeq \frac{192}{(4N+3)^2} \simeq 0.0033$

$\delta T/T \sim 10^{-5} \quad \Rightarrow \quad \frac{\xi}{\sqrt{\lambda}} \sim 47000$

Note: for very near critical top quark/Higgs masses results change and allow for larger $r$
Vacuum decays by creating bubbles of true vacuum, which then expand very fast ($v \to c$).

\[ \rho_{\text{decay}} \propto e^{-S_{\text{bounce}}} \sim e^{-\frac{8\pi^8}{3\lambda(h)}} \]

**Note on Planck corrections**

- Critical bubble size $\sim$ Planck scale
- Potential corrections $V_{\text{Planck}} = \pm \frac{\phi^n}{M_P^{n-4}}$ change lifetime!

Only $+$ sign is allowed for Planck scale corrections!
As far as we are “safe” now (i.e. at low energies), what about Early Universe?
What happens with the Higgs boson at inflation?

- if Higgs boson is completely separate from inflation
- if Higgs boson interacts with inflaton/gravitation background
- if Higgs boson drives inflation
Metastable vacuum during inflation *is* dangerous

- Let us suppose Higgs is not at all connected to inflationary physics (e.g. $R^2$ inflation)
- All fields have vacuum fluctuation
- Typical momentum $k \sim H_{\text{inf}}$ is of the order of Hubble scale
- If typical momentum is greater than the potential barrier – SM vacuum would decay if
  $$H_{\text{inf}} > V_{\text{max}}^{1/4}$$

Most probably, fluctuations at inflation lead to SM vacuum decay...

- Observation of any tensor-to-scalar ratio $r$ by CMB polarization missions would mean great danger for metastable SM vacuum!
Measurement of primordial tensor modes determines scale of inflation

$$H_{\text{inf}} = \sqrt{\frac{V_{\text{infl}}}{3M_{\text{P}}^2}} \sim 8.6 \times 10^{13} \text{GeV} \left( \frac{r}{0.1} \right)^{1/2}$$
Does inflation contradict metastable EW vacuum?

- Higgs interacting with inflation can cure the problem.
  Examples
  - Higgs ($\phi$)–inflaton ($\chi$) interaction may stabilize the Higgs
    \[ L_{\text{int}} = -\alpha \phi^2 \chi^2 \]
  - Higgs-gravity *negative* non-minimal coupling stabilizes Higgs in de-Sitter (inflating) space
    \[ L_{\text{nm}} = \xi \phi^2 R \]
- New physics *below* $\mu_0$ may remove Planck scale vacuum and make EW vacuum stable – many examples
New physics \textit{above} $\mu_0$ may solve the problem

\begin{itemize}
  \item Minimum at Planck scale should be removed (but can remain near $\mu_0 \sim 10^{10}$ GeV)
  \item Reheating after inflation should be fast.
\end{itemize}

No need for new physics at “low” ($< \mu_0$) scales!

Example: Higgs inflation with threshold corrections at $M_p/\xi$
After inflation symmetry is restored in preheating

- Thermal potential removes the high scale vacuum
- Universe cools down to EW vacuum
Higgs inflation and radiative corrections

\[ S_J = \int d^4x \sqrt{-g} \left\{ -\frac{M_P^2}{2} R - \frac{\xi h^2}{2} R + g_{\mu\nu} \frac{\partial^\mu h \partial^\nu h}{2} - \frac{\lambda}{4} (h^2 - v^2)^2 \right\} \]

Term \( \xi h^2 R \) makes potential flat

Threshold corrections at scale \( M_P / \xi \)

"shift" \( \lambda \) back to positive values

(Not really to scale)
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Conclusions

- The scale of new physics is yet unknown!
- If all new physics is below EW scale, intriguing relations between Planck scale and Electroweak physics are possible,

  - Precise measurements of the SM parameters
    - Lepton collider – top quark mass (Yukawa)
    - Higgs boson mass and properties
  - Cosmology – inflationary parameters, especially tensor-to-scalar ratio

And search for new physics at low scale!

- SHIP – search for new light particles – heavy sterile neutrinos
- FCC – search for sterile neutrinos with larger masses
- Astrophysics – search for X-rays from decaying Dark Matter
Line in the X-ray signal can mean 7 keV DM
With rise and falls is still there for more than a year

Signal in Perseus cluster

Sterile neutrino $N_1$ parameters required

Data by Chandra and XMM-Newton,
Bulbul et.al’13, Boyarsky et.al’13

FIG. 1: Left: Folded count rate (top) and residuals (bottom) for the MOS spectrum of the central region of M31. Statistical Y-errorbars on the top plot are smaller than the point size. The line around 3.5 keV is not added, hence the group of positive residuals. Right: zoom onto the line region.
Search for $N_{2,3}$ is possible

- Leptogenesys by $N_{2,3}$
  \[ \Delta M/M \sim 10^{-3} \]

- Experimental searches
  - $N_{2,3}$ production in hadron decays (LHCb):
    - Missing energy in $K$ decays
    - Peaks in Dalitz plot
  - $N_{2,3}$ decays into SM
    - Beam target: SHiP
    - High luminosity lepton collider at $Z$ peak

Note: Other related models (e.g. scalars for DM generation, light inflaton) also show up in such experiments
RG running indicates small $\lambda$ at Planck scale

Renormalization evolution of the Higgs self coupling $\lambda$

\[ \lambda \approx \lambda_0 + b \ln^2 \frac{\mu}{q} \]

\[ b \approx 0.000023 \]

$\lambda_0$ - small

$q$ of the order $M_p$

depend on $M^*_h$, $m^*_t$

\[
\begin{align*}
(4\pi)^2 \frac{\partial \lambda}{\partial \ln \mu} &= 24\lambda^2 - 6y_t^4 \\
&\quad + \frac{3}{8} \left(2g_2^4 + (g_2^1 + g_1^2)^2\right) \\
&\quad + (-9g_2^2 - 3g_1^2 + 12y_t^2)\lambda
\end{align*}
\]

Higgs mass $M_h = 125.3 \pm 0.6$ GeV
RG running indicates small $\lambda$ at Planck scale

Potentials in different regimes

$$\lambda \simeq \lambda_0 + b \ln^2 \frac{\mu}{q}$$

$$b \simeq 0.000023$$

$\lambda_0$ - small

$q$ of the order $M_p$

$$\{ \text{depend on } M^*_h, \ m^*_{\lambda_0} \}$$

$$U(\chi) \simeq \frac{\lambda(\mu)M_P^4}{4\xi^2} \left( 1 - e^{-\frac{2\chi}{\sqrt{6}M_P}} \right)^2$$

$$\mu^2 = \alpha^2 \frac{y_t(\mu)^2}{2} \frac{M_P^2}{\xi} \left( 1 - e^{-\frac{2\chi}{\sqrt{6}M_P}} \right)$$
Interesting inflation near to the critical point

Parameters in particle physics: \( \lambda_0, q, \xi \)

\begin{align*}
\kappa \sim q \sqrt[4]{\xi} \frac{\sqrt{2}}{M_P} \frac{y_t}{y_t} \\
\text{For given } r \text{ (or } \xi) \text{ very small change of } \kappa \text{ (or } M_h^*) \text{ gives any } n_s
\end{align*}