The Higgs field and the early universe

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BROOKHAVEN
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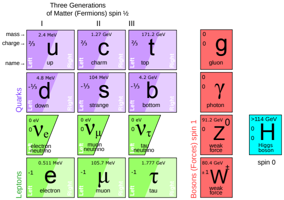
Outline

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 $\sim 125\,\text{GeV}$ – 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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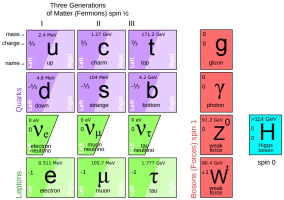

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Einstein gravity

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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)

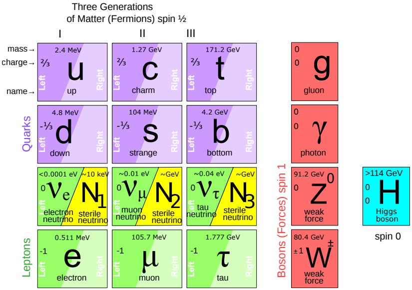
Laboratory also asks for SM extensions

- Neutrino oscillations

Nothing really points to a definite scale above EW

- Neutrino masses and oscillations (absent in SM)
  - Right handed neutrino between 1 eV and 10^{15} GeV
- Dark Matter (absent in SM)
  - Models exist from 10^{-5} eV (axions) up to 10^{20} GeV (Wimpzillas, Q-balls)
- Baryogenesys (absent in SM)
  - Leptogenesys scenarios exist from $M \sim 10$ MeV up to 10^{15} GeV

Possible: New physics only at low scales – νMSM



Role of sterile neutrinos

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

$N_{2,3}$ $M_{2,3} \sim$ several GeV:
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

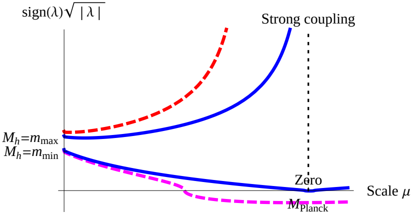
- Absolutely stable Electroweak vacuum
- Metastable EW vacuum (true vacuum at/above Planck scale)

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 couplign to gravity)

Standard Model self-consistency and Radiative Corrections

- Higgs self coupling constant λ changes with energy due to radiative corrections.



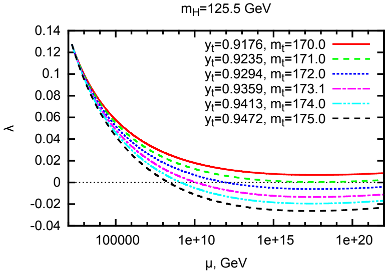
$$(4\pi)^2\beta_\lambda = 24\lambda^2 - 6y_t^4 + \frac{3}{8}(2g_2^4 + (g_2^2 + g_1^2)^2) + (-9g_2^2 - 3g_1^2 + 12y_t^2)\lambda$$

- Behaviour is determined by the masses of the Higgs boson $m_H = \sqrt{2\lambda}\, v$ and other heavy particles (top quark $m_t = y_t v/\sqrt{2}$)
- If Higgs is heavy $M_H > 170$ GeV – the model enters *strong coupling* at some low energy scale – new physics required.

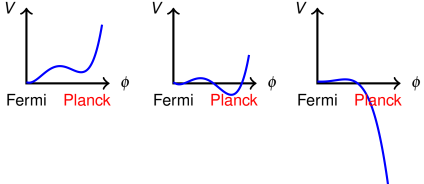
Lower Higgs masses: RG corrections push Higgs coupling to negative values

- For Higgs masses $M_H < M_{\text{critical}}$ coupling constant is negative above some scale μ_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?

Coupling λ evolution:



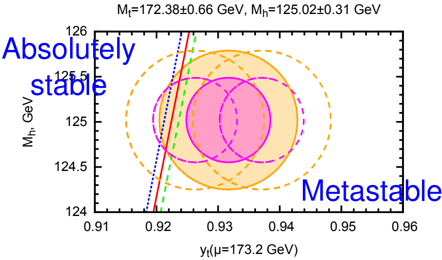
Higgs potential $V(\phi) \simeq \lambda(\phi)\frac{\phi^4}{4}$

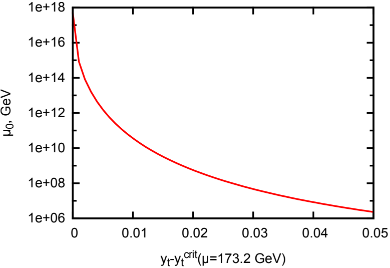


LHC result: SM is definitely perturbative up to Planck scale, and probably has metastable SM vacuum

Experimental values for y_t

Scale μ_0 for $\lambda(\mu_0) = 0$

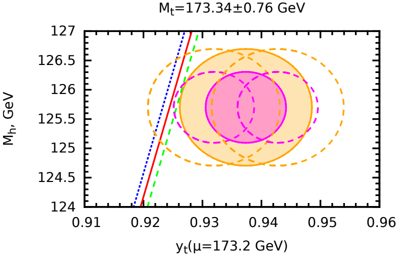


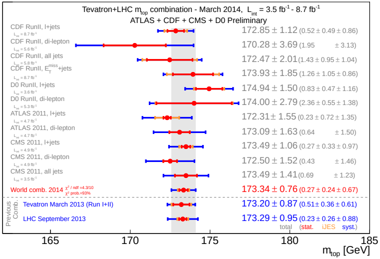


We live close to the metastability boundary – but on which side?!

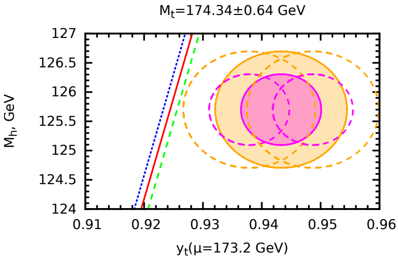
Future measurements of top Yukawa and Higgs mass are essential!

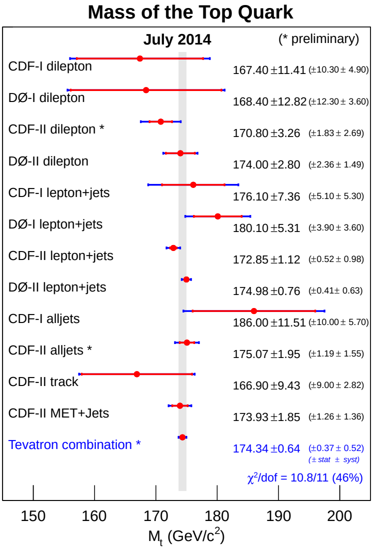
March 2014 – metastable?



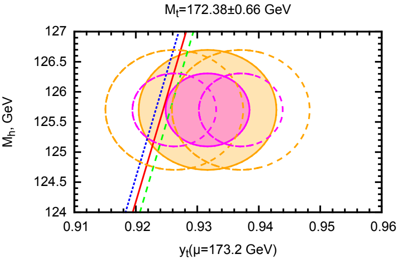


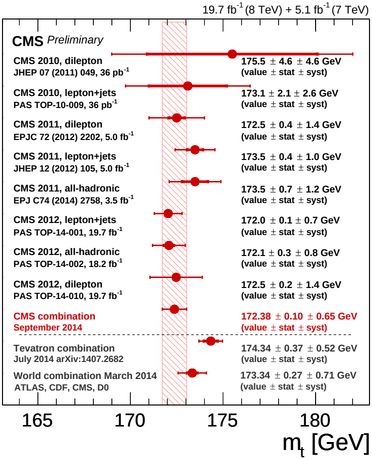
July 2014 – oh, very metastable!





September 2014 – hmm, maybe stable is ok?

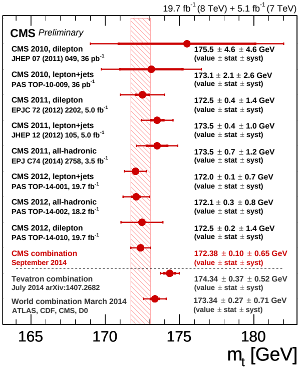




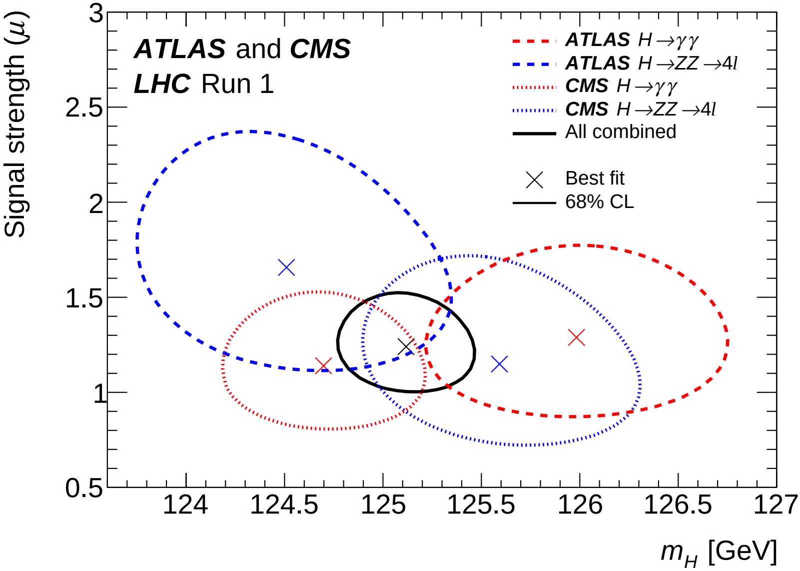
Determination of top quark Yukawa

- Hard to determine mass in the events
- Hard to relate the “pole” (the same for “Mont-Carlo”) mass to the $\overline{\text{MS}}$ 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



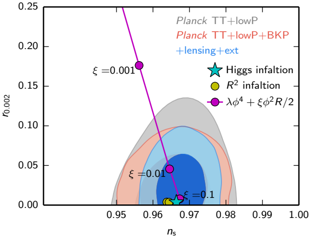
- Experiment (measurements of SM masses) – We are somewhere close to the boundary between stability and metastability
- Stable Electroweak vacuum – looks safe
- Metastable – is it ok?

Stable SM vacuum	inflaton = Higgs	inflaton & Higgs independent	inflaton & Higgs interacting
Large r	Yes (threshold corr.)	Yes	Yes
Small r	Yes	Yes	Yes
Planck scale corections	Scale inv.	Any	Any

Metastable SM vacuum	inflaton = Higgs	inflaton & Higgs independent	inflaton & Higgs interacting
Large r	No	No	Yes Model dep.
Small r	Yes (threshold corr.)	Yes $r < 10^{-9}$	Yes Model dep.
Planck scale corections	Scale inv.	Restricted	Model dep.

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



Higgs inflation at tree level

Scalar part of the (Jordan frame) action

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

- 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 $v \ll M_P/\sqrt{\xi}$ – can be neglected in the early Universe
- At $h \gg M_P/\sqrt{\xi}$ *all* masses are proportional to h – scale invariant spectrum!

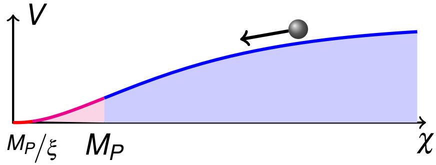
Higgs inflation at tree level

Scalar part of the (Jordan frame) action

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

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

$$\frac{\sqrt{\lambda}}{\xi} = \frac{1}{49000}$$

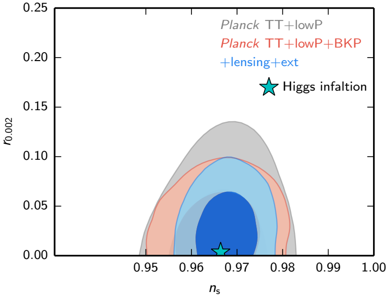


Mathematical trick – conformal transformation

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

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

CMB parameters are predicted



For large ξ Higgs inflation

spectral index $n \simeq 1 - \frac{8(4N+9)}{(4N+3)^2} \simeq 0.97$

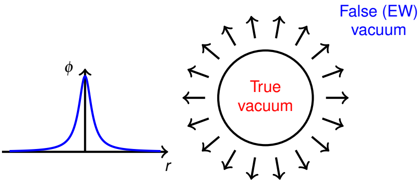
tensor/scalar ratio $r \simeq \frac{192}{(4N+3)^2} \simeq 0.0033$

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

Note: for very near critical top quark/Higgs masses results change and allow for larger r

What to do if we are metastable?

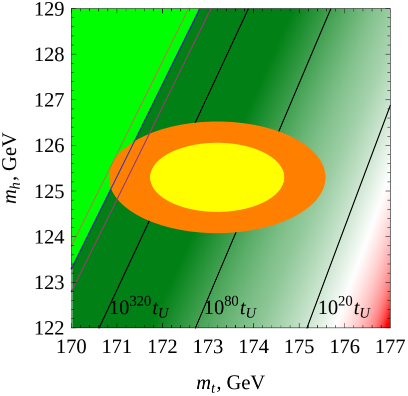
Vacuum decays by creating bubbles of true vacuum, which then expand very fast ($v \to c$)



Tunneling suppression:

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

Lifetime ≫ age of the Universe!



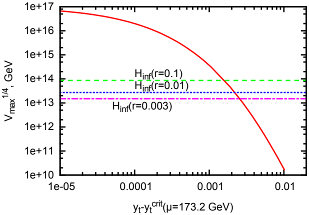
Note on Planck corrections

- 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 fileds 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

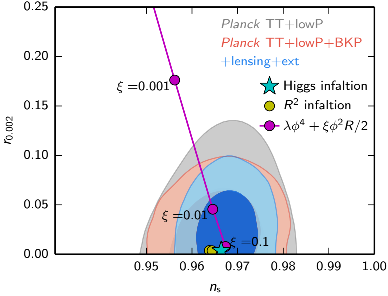
$$H_{\text{inf}} > V_{\text{max}}^{1/4}$$

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

$$H_{\mathrm{inf}} = \sqrt{\frac{V_{\mathrm{infl}}}{3M_P^2}} \sim 8.6 \times 10^{13}\,\mathrm{GeV}\left(\frac{r}{0.1}\right)^{1/2}$$



Does inflation contradict metastable EW vacuum?

- Higgs interacting with inflation can cure the problem. Examples
  - Higgs (ϕ)–inflaton (χ) 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* μ_0 may remove Planck scale vacuum and make EW vacuum stable – many examples

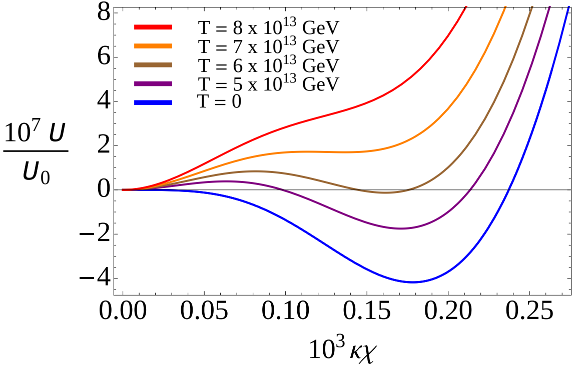
New physics *above* μ_0 may solve the problem

Requirements

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

No need for new physics at “low” ($< \mu_0$) scales!
Example: Higgs inflation with threshold corrections at M_p/ξ

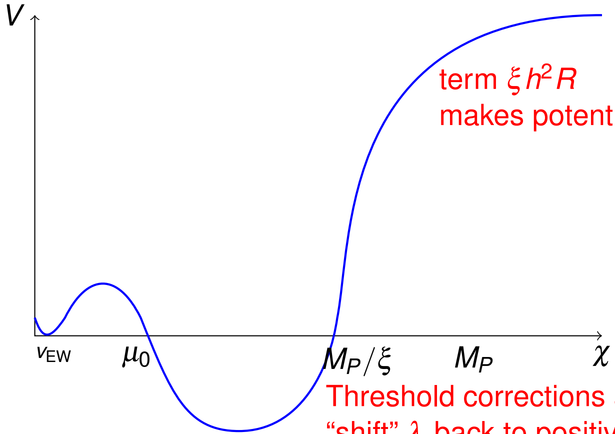
After inflation symmetry is restored in preheating



- Thermal potential removes the high scale vacuum
- Universe cools down to EW vacuum

Higgs inflation and radiative corrections

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



term $\xi h^2 R$
makes potential flat

Threshold corrections at scale M_P/ξ
“shift” λ back to positive values

(Not really to scale)

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Planck scale corections	Scale inv.	Restricted	Model dep.

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 paramters
    - Lepton collider – top quark mass (Yukawa)
    - Higgs boson mass and properties
- Cosmology – inflationary parameters, especially tensor-to-scalar ratio

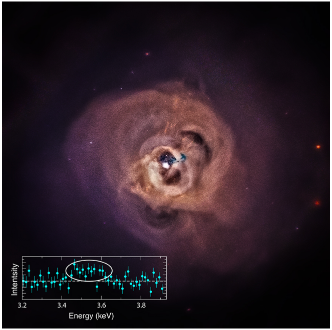
And search for new physics at low scale!

- 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

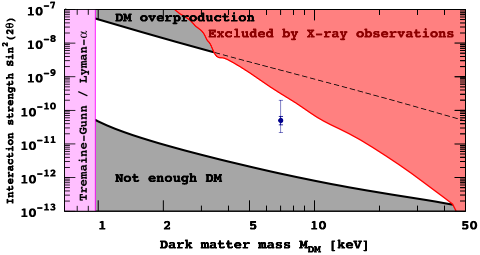
With rise and falls is still there for more than a year

Signal in Perseus cluster



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

Sterile neutrino N_1 parameters required



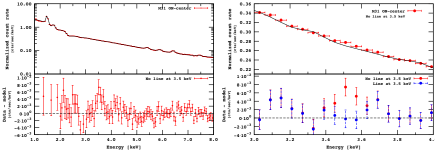
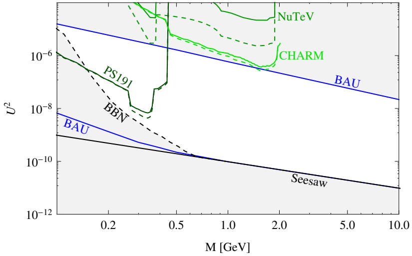


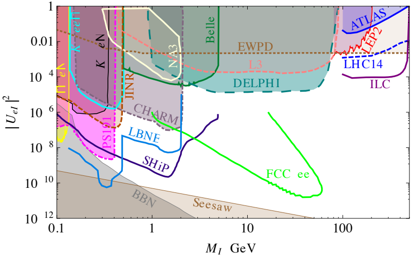
FIG. 1: *Left:* Folded count rate (top) and residuals (bottom) for the MOS spectrum of the central region of M31. Statistical Y-errorbars on the top plot are smaller than the point size. The line around 3.5 keV is *not added*, hence the group of positive residuals. *Right*: zoom onto the line region.

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



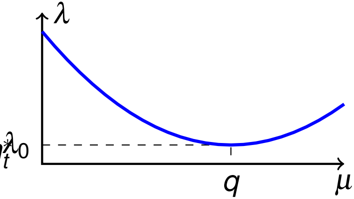


RG running indicates small λ at Planck scale

Renormalization evolution of the Higgs self coupling λ

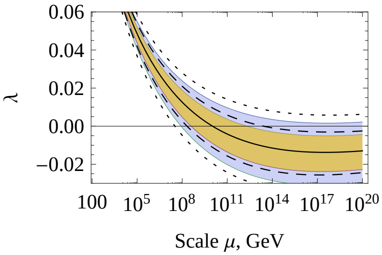
$$\lambda \simeq \lambda_0 + b \ln^2 \frac{\mu}{q}$$

$$\left.\begin{array}{l} b \simeq 0.000023 \\ \lambda_0 - \text{small} \\ q \text{ of the order } M_p \end{array}\right\} \text{depend on } M_h^*,\ m_t^*$$



$$(4\pi)^2 \frac{\partial \lambda}{\partial \ln \mu} = 24\lambda^2 - 6y_t^4 + \frac{3}{8}(2g_2^4 + (g_2^2 + g_1^2)^2) + (-9g_2^2 - 3g_1^2 + 12y_t^2)\lambda$$

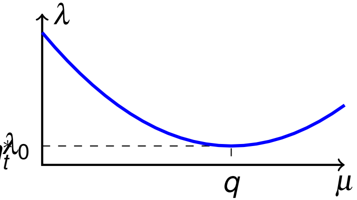
Higgs mass M_h=125.3±0.6 GeV



RG running indicates small λ at Planck scale

Potentials in different regimes

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

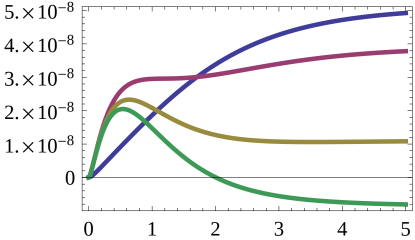


$b \simeq 0.000023$

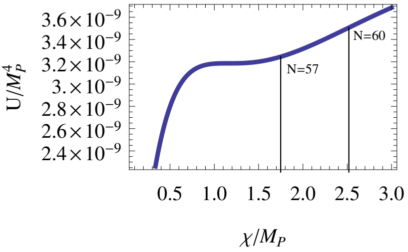
$$\left.\begin{array}{l} \lambda_0 - \text{small} \\ q \text{ of the order } M_p \end{array}\right\} \text{depend on } M_h^*,\ m_t^*$$

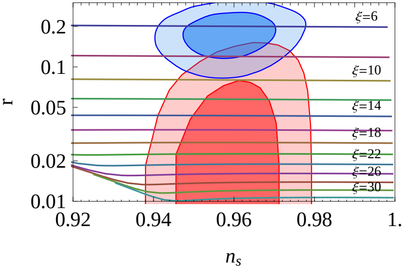
$$U(\chi) \simeq \frac{\lambda(\mu) M_P^4}{4\xi^2}\left(1 - e^{-\frac{2\chi}{\sqrt{6}M_P}}\right)^2$$

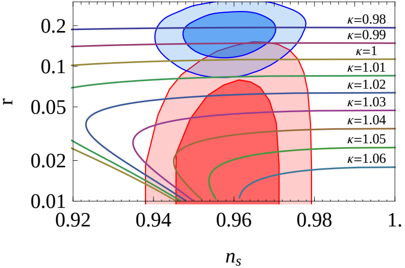
$$\mu^2 = \alpha^2 \frac{y_t(\mu)^2}{2}\frac{M_P^2}{\xi}\left(1 - e^{-\frac{2\chi}{\sqrt{6}M_P}}\right)$$



Interesting inflation near to the critical point







Parameters in
particle physics: λ_0, q, ξ
cosmology: $\mathscr{P}_R, r, n_s$

$\kappa \sim q\frac{\sqrt{\xi}}{M_P}\frac{\sqrt{2}}{y_t}$

For given r (or ξ) very small change of κ (or M_h^*) gives any n_s