ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Particle Physics and Cosmology

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Das Land Steiermark
Wissenschaft und Forschung

UNI GRAZ

NAWI Graz

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New Trends in Particle Physics, Quantum Gravity & Cosmology

Outline

Lecture 1: What are the problems and ideas for solutions?

- Structure of the Universe at large scales: flatness, horison, etc
  - Inflationary Universe
- Charge asymmetry of the Universe
  - Baryogenesis
- Rotational curves of galaxies, matter content, large scale structure
  - Particle Dark Matter

Outline

Lecture 2

- The current scene: LHC and ΛCDM
- Vacuum meta(?) stability
- Minimal physics for inflation: Higgs as an inflaton

Lecture 3

- Minimal physics for neutrino masses
- Baryogenesis
- Dark Matter
- Conclusions

The scene

There are hundreds of proposals for the models of inflations, for baryogenesis, and for particle dark matter candidates

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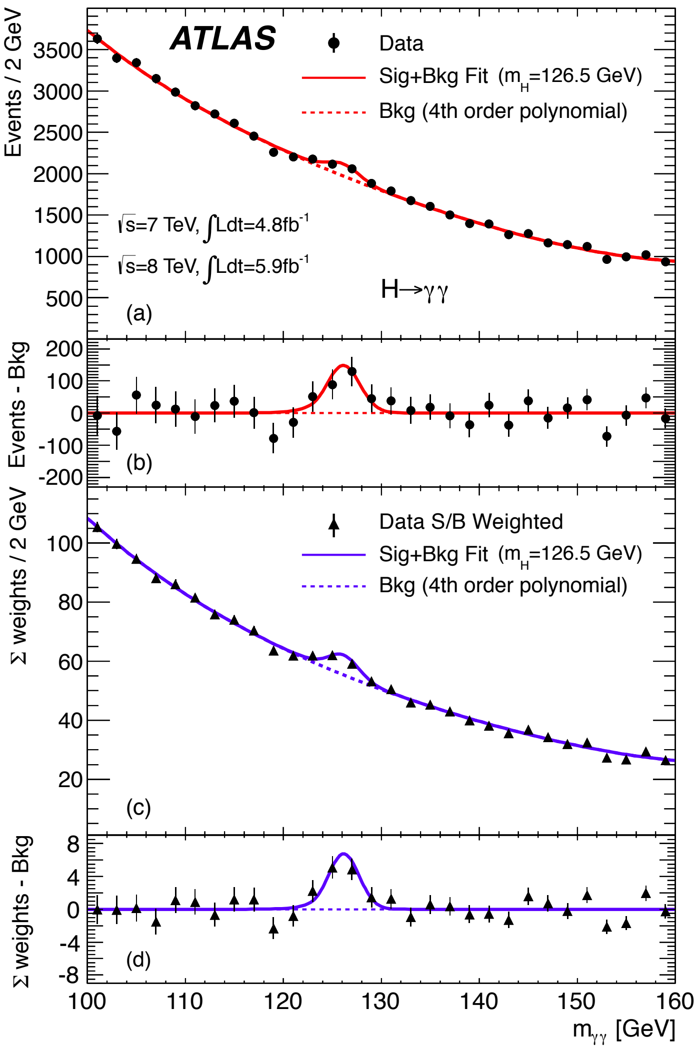
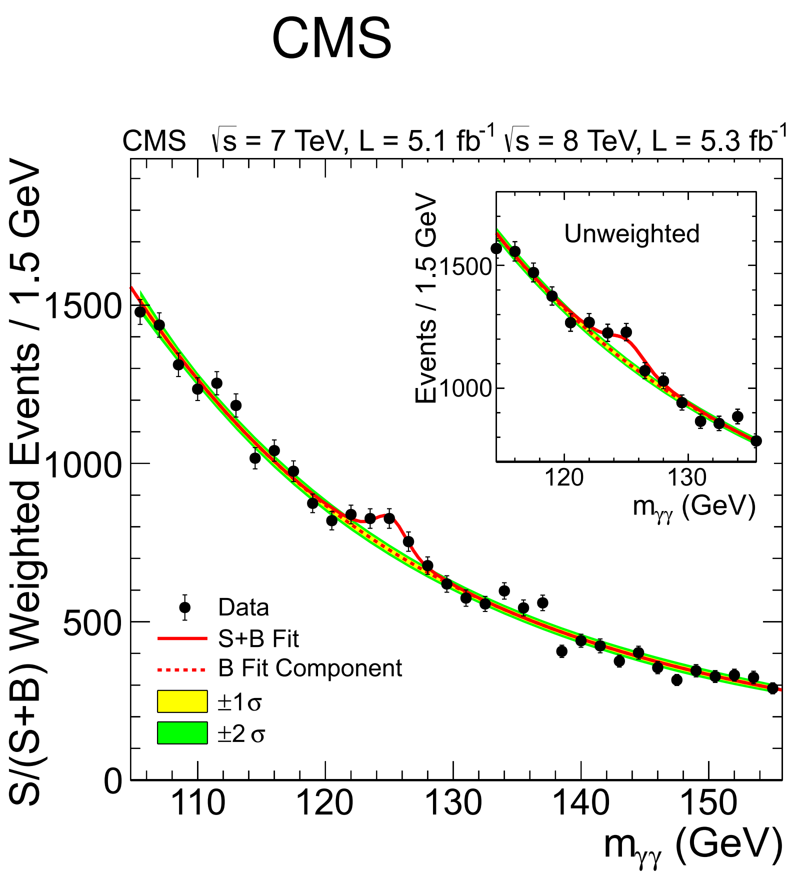
LHC discoveries important for Cosmology

July 4, 2012, Higgs at ATLAS and CMS

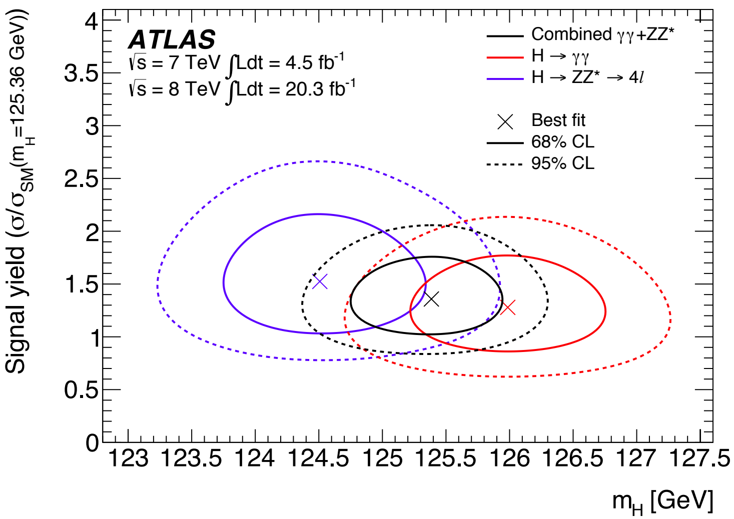


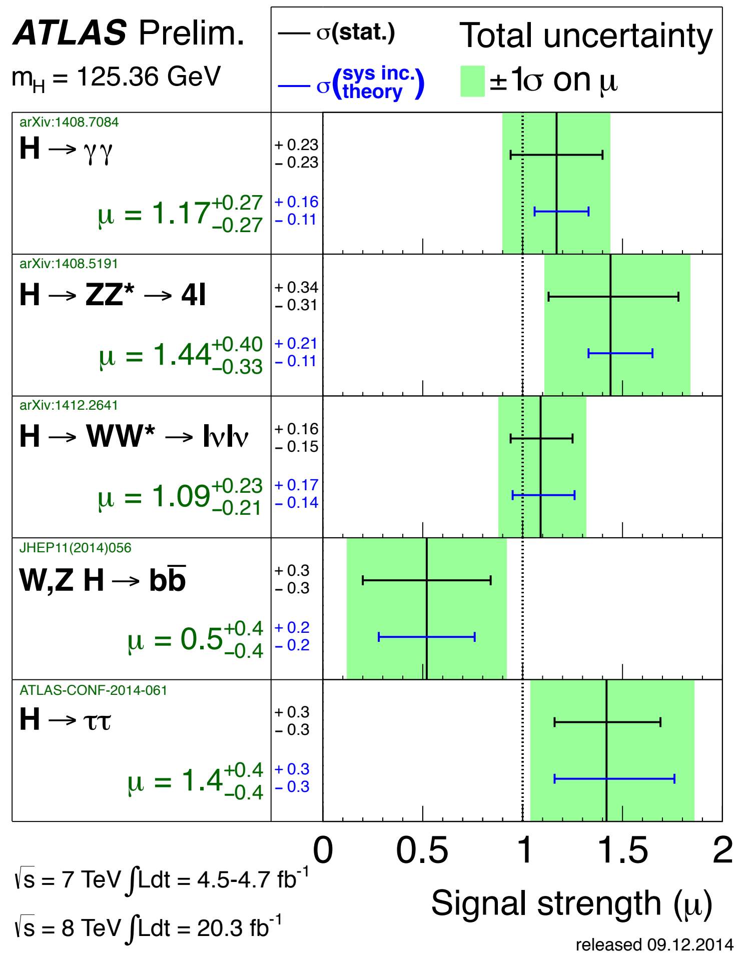


Higgs boson properties

Atlas - $M_H = 125.36 \pm 0.41$ GeV

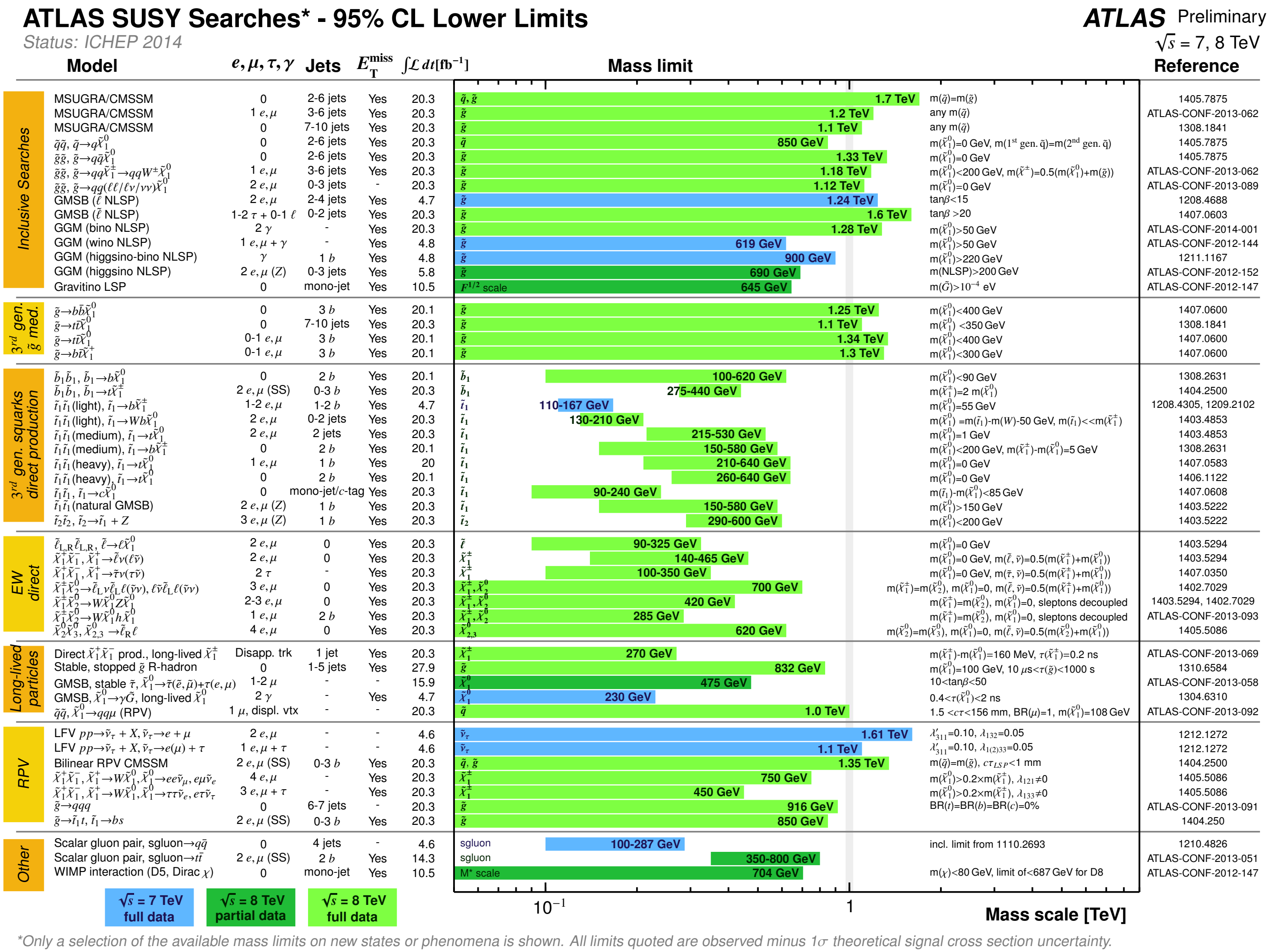
CMS - $M_H = 125.03 \pm 0.29$ GeV



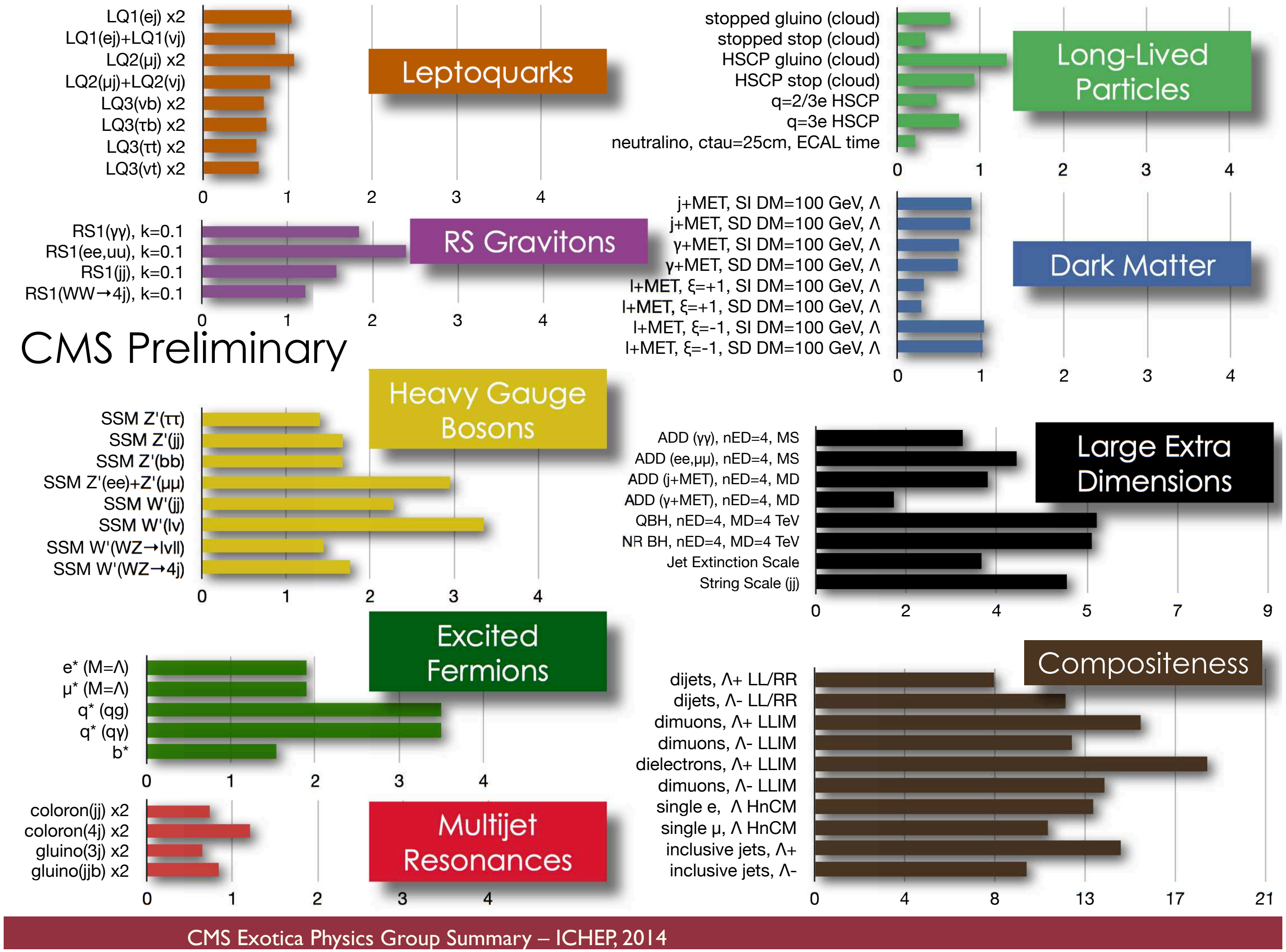


New resonance properties are consistent with those of the Higgs boson of the Standard Model

Searches for new physics, SUSY

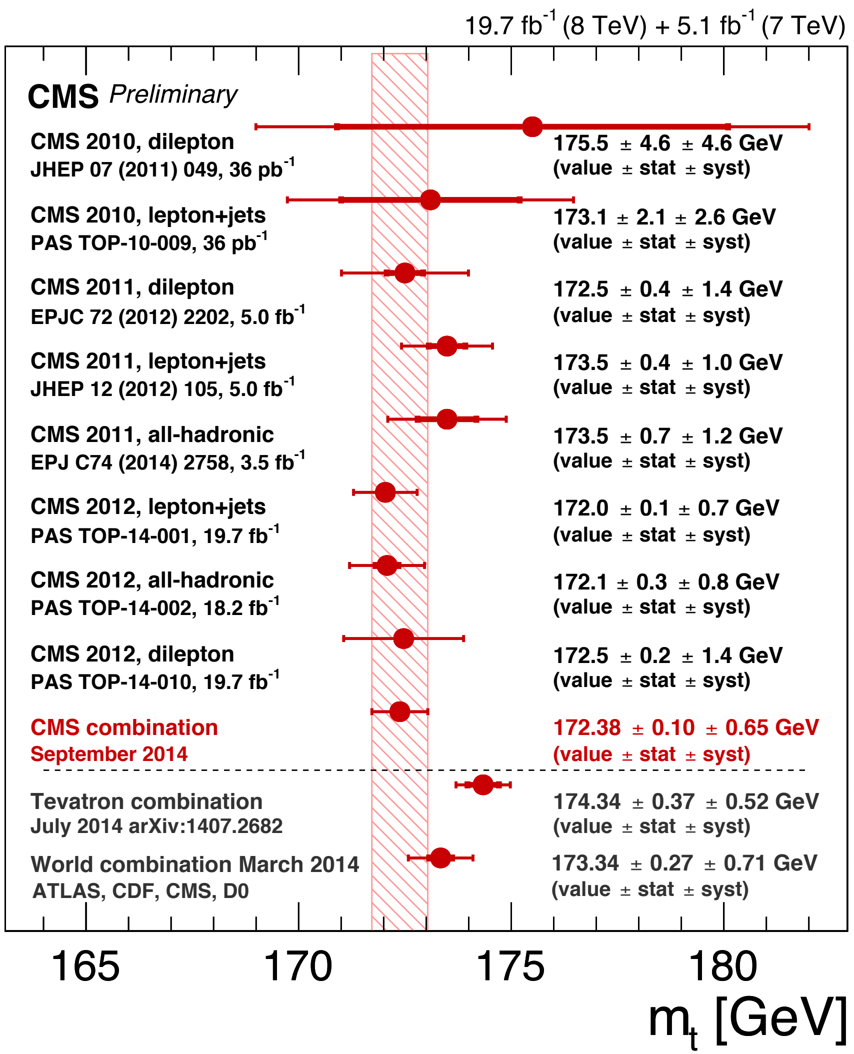


Searches for new physics, exotics



Determination of top quark mass

Monte Carlo mass: $m_t = 172.38 \pm 0.10 \pm 0.65$ GeV



Summary of the LHC findings

- The Standard Model in now complete: the last particle - Higgs boson, predicted by the SM, has been found

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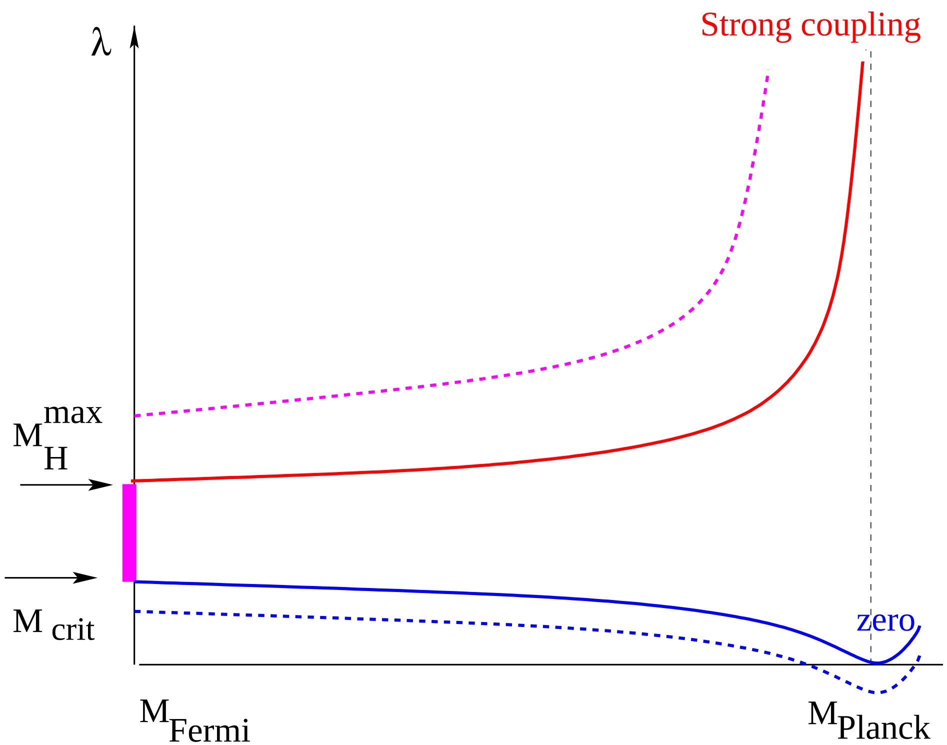
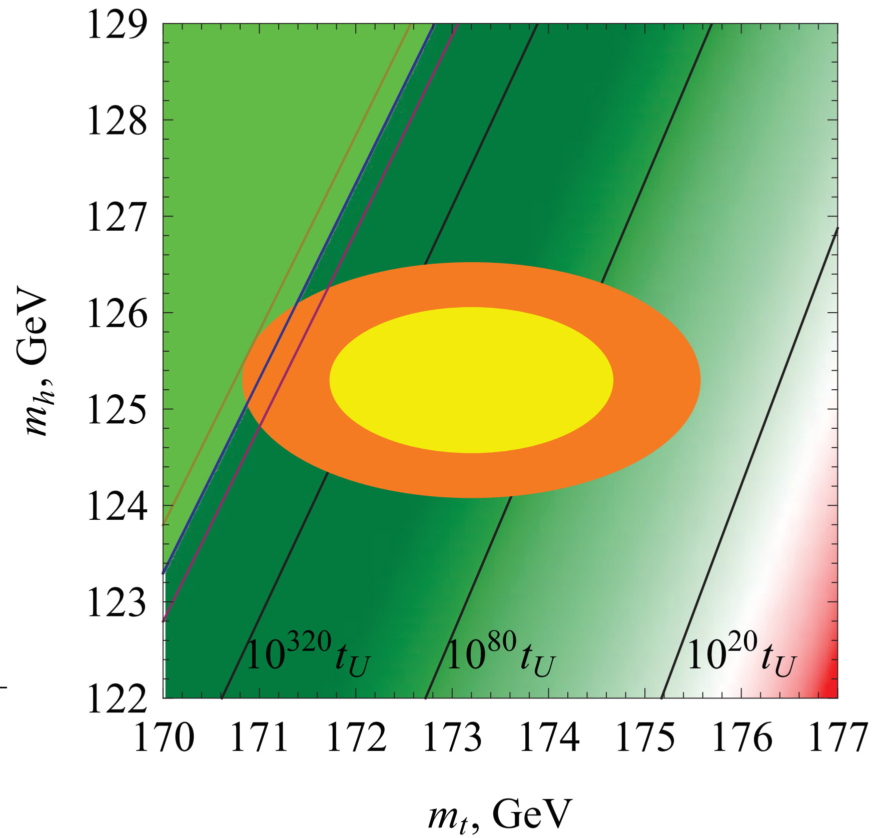
- The Standard Model in now complete: the last particle - Higgs boson, predicted by the SM, has been found
- No deviations from the SM have been observed (750 diphoton excess?)
- The masses of the top quark and of the Higgs boson, the Nature has chosen, make the SM a self-consistent effective field theory all the way up to the Planck scale
  $114 \text{ GeV} < m_H < 175 \text{ GeV}$

Behaviour of the scalar self-coupling

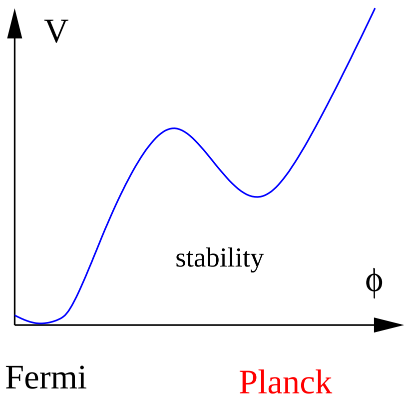
vacuum lifetime

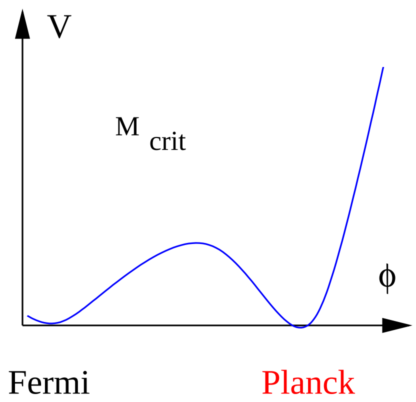


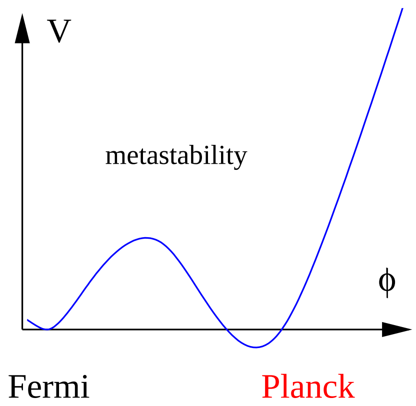


Vacuum (meta?)stability

Important fact: The combination of top-quark and Higgs boson masses is very close to the stability bound of the SM vacuum* (95'), to the Higgs inflation bound** (08'), and to asymptotic safety values for M_H and M_t *** (09'):





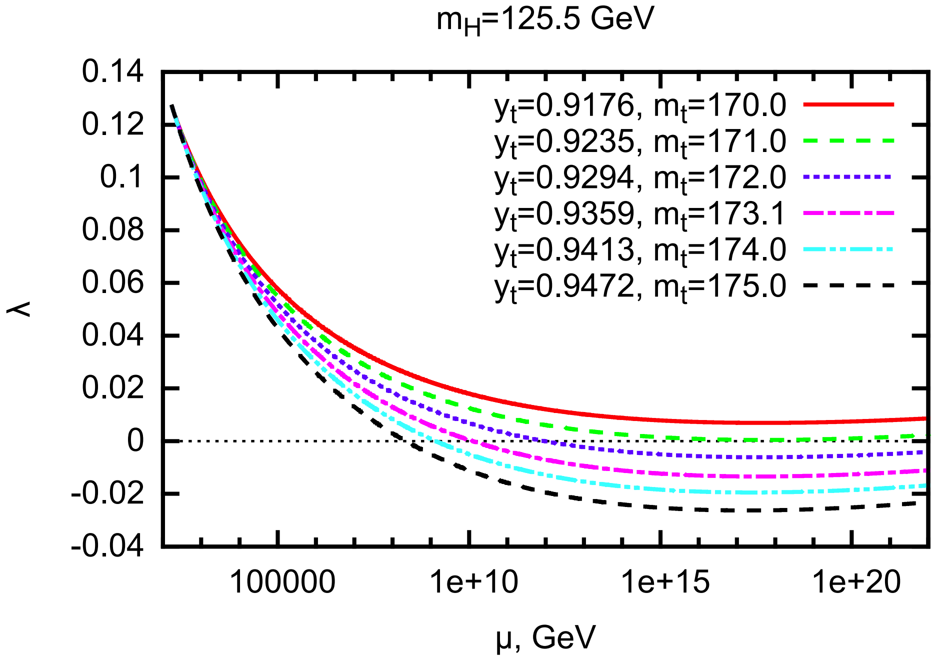


* Froggatt, Nielsen

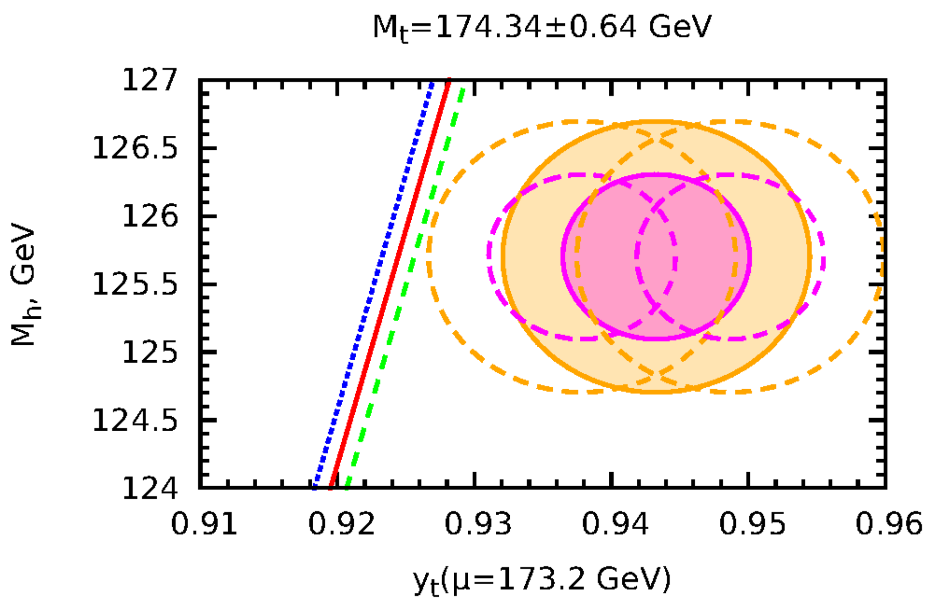
** Bezrukov, MS

De Simone, Hertzberg, Wilczek

*** Wetterich, MS

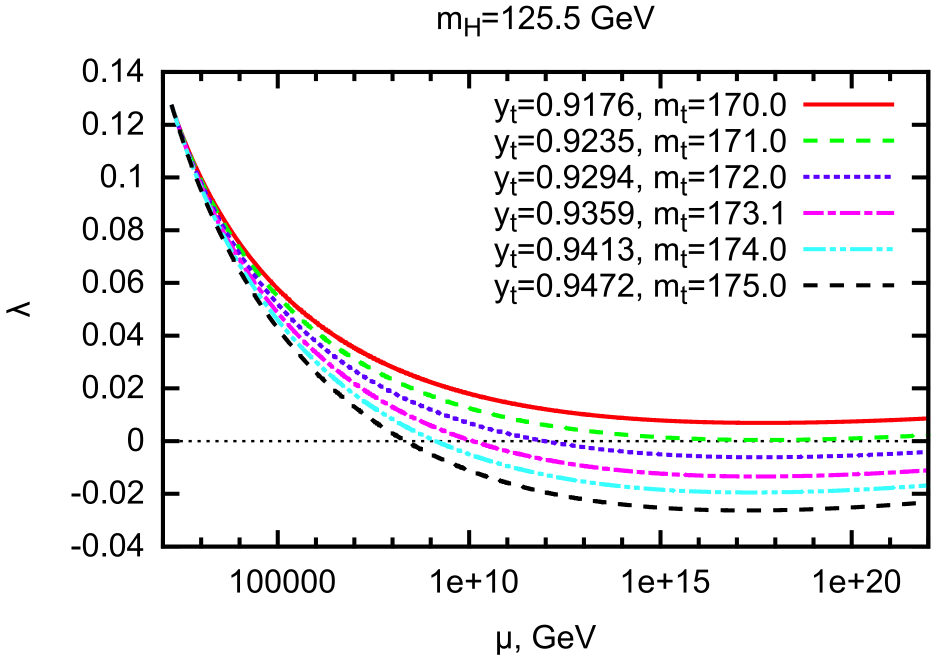


Absolute stability



Metastability

TEVATRON 2014: $m_t = \mathbf{174.34 \pm 0.37 \pm 0.52\ GeV}$



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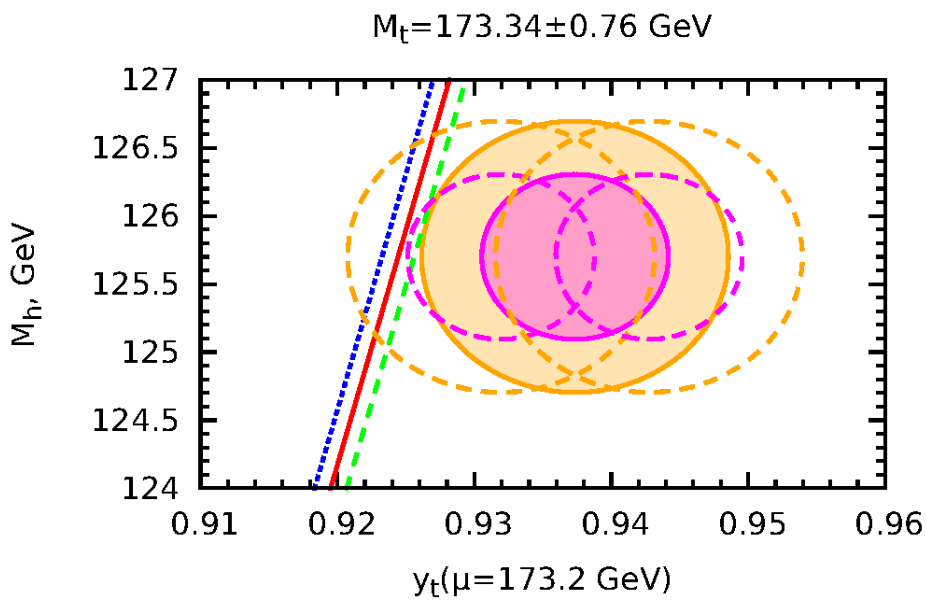
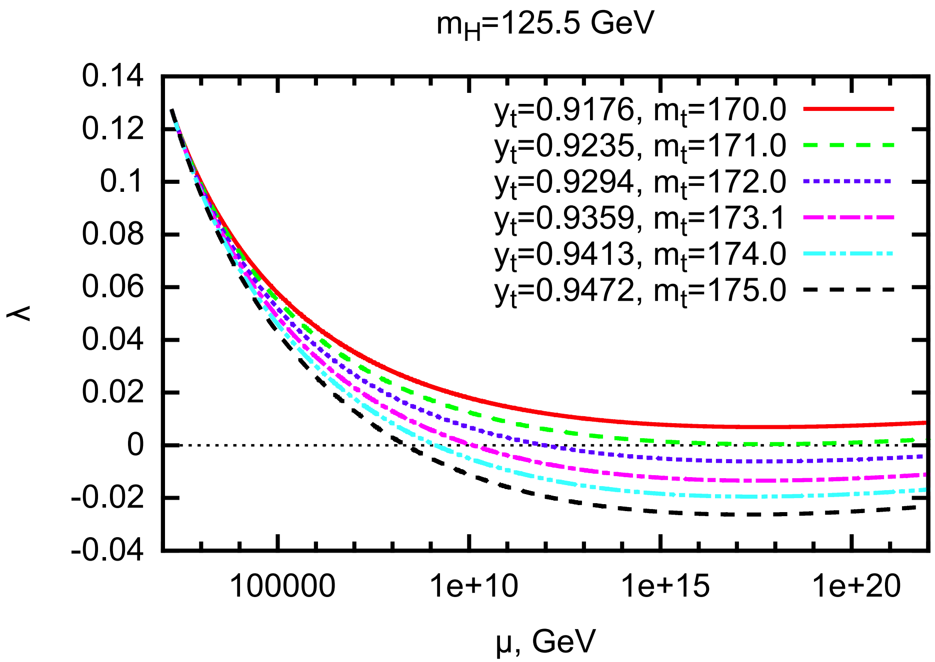
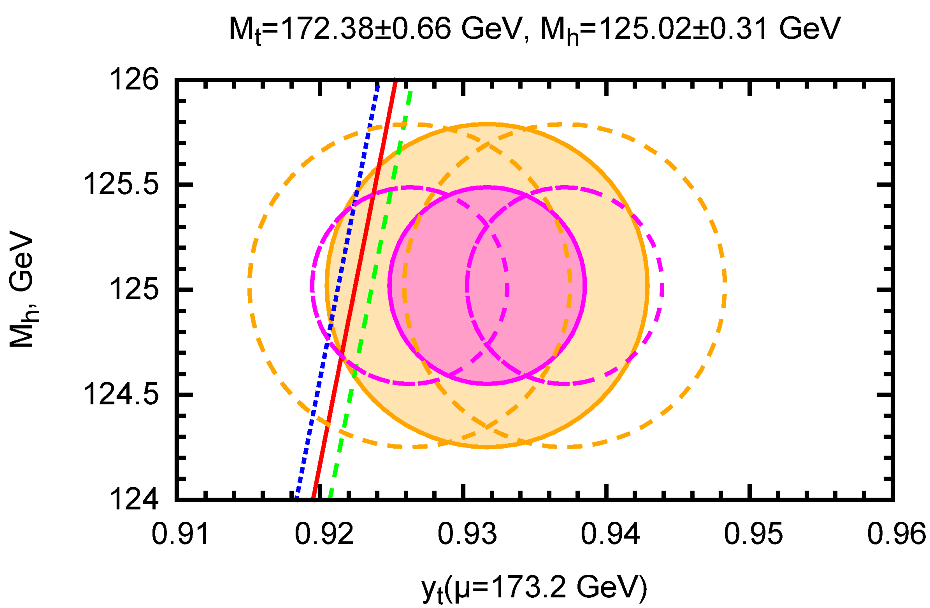


Metastability

PDG 2014: $m_t = \mathbf{173.34 \pm 0.27 \pm 0.71\ GeV}$



Absolute stability



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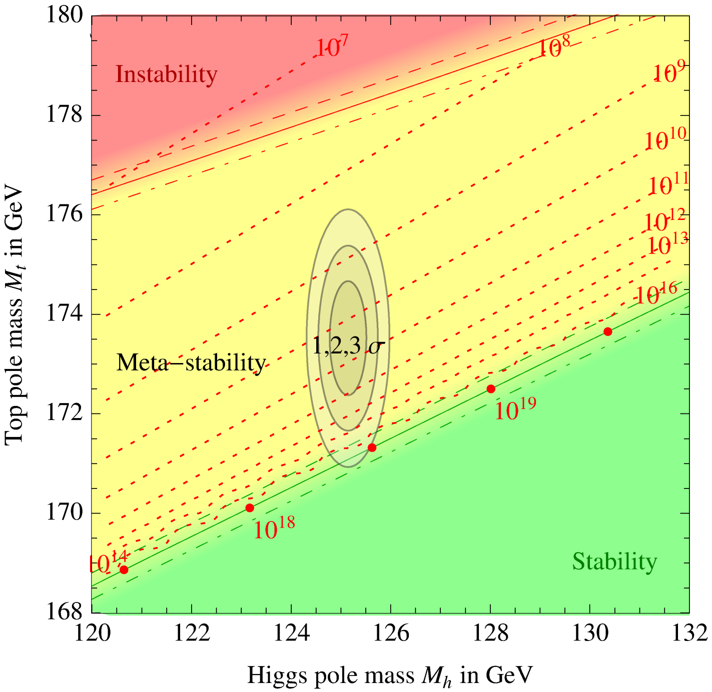
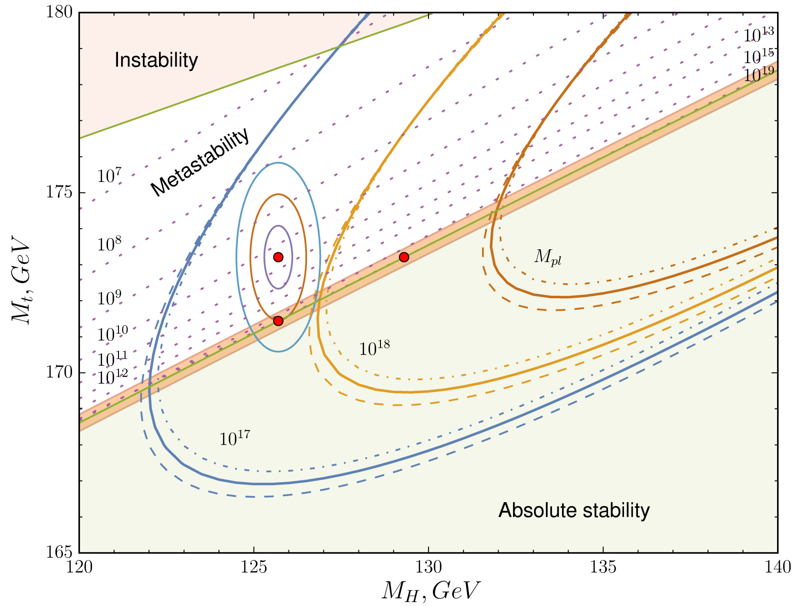
CMS 2014: $m_t = \mathbf{172.38 \pm 0.10 \pm 0.65\ GeV}$

Buttazzo et al, '13, '14



Bednyakov et al, '15

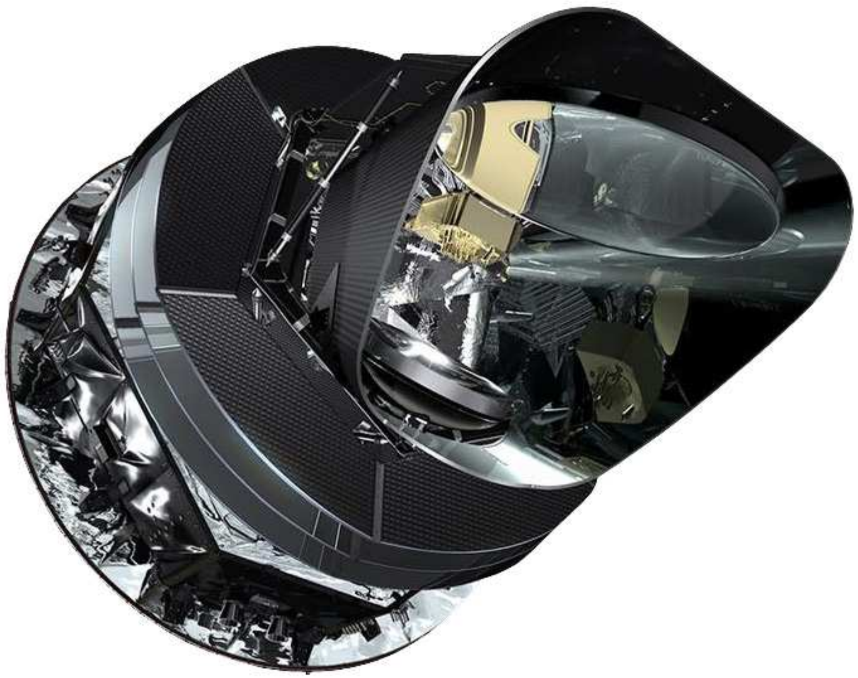


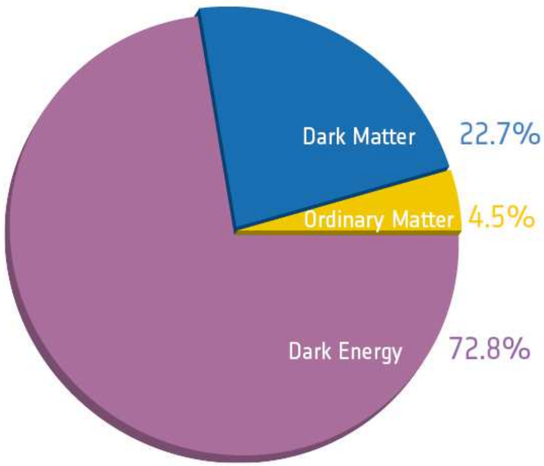
Vacuum is unstable at $\mathbf{2.8\sigma}$

Vacuum is unstable at $\mathbf{1.3\sigma}$

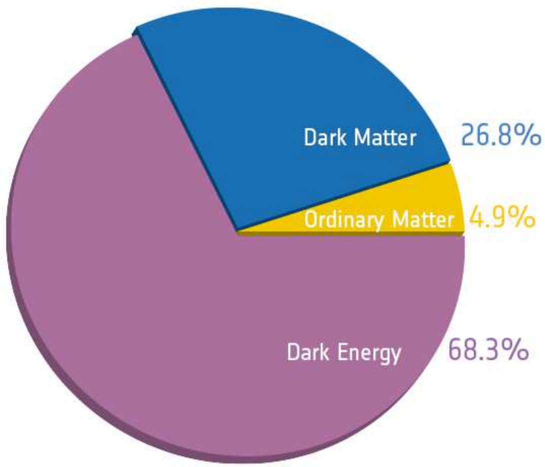
Main uncertainty: top Yukawa coupling, relation between the MC mass and the top Yukawa coupling allows for ± 1 GeV in M_{top}. Alekhin et al, Frixione et al.

Planck results

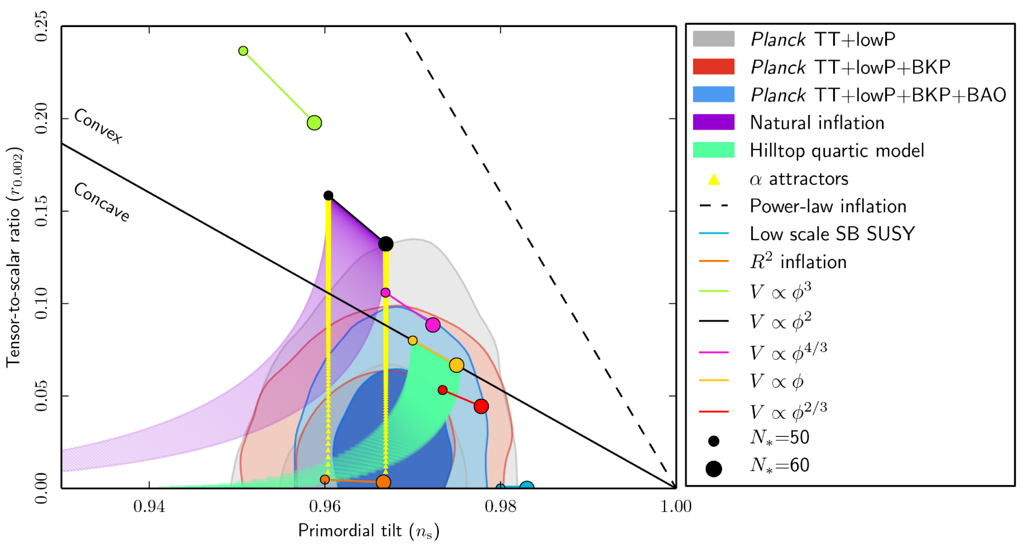




Before Planck



After Planck



The message from Planck: The Standard ΛCDM model is in a very good agreement with the data

- No primordial non-Gaussianities are observed
- One-field inflationary models agree well with Planck
- No physics beyond Standard ΛCDM is observed

Observational evidence for BSM physics

- The Universe is flat, homogeneous and isotropic at large scales, but contains structures such as galaxies at smaller distances. Cosmological inflation is needed to explain this.

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- Most of the matter in the universe is dark : no particle physics candidate in the SM
- Neutrino masses and oscillations, absent in the Standard Model
- The Universe expansion at present is accelerating. Is this simply a tiny cosmological constant or something more complicated?

How to reconcile the evidence for new physics without spoiling the success of the Standard Model and Standard ΛCDM?

Inflation

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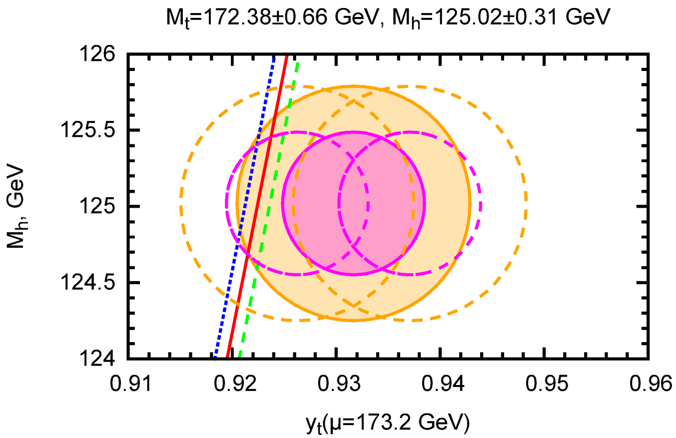
- Ockham's razor in action, 3 step logic:
- For inflation we better have scalar field
- The Higgs boson was predicted by the SM and finally has been discovered
- Let's use it for inflation!

Higgs inflation near the critical line



Higgs Inflation, no loops

Higgs field in general must have non-minimal coupling to gravity:

$$S_G = \int d^4x\sqrt{-g}\left\{ -\frac{M_P^2}{2}R - \frac{\xi h^2}{2}R \right\}$$

Jordan, Feynman, Brans, Dicke,...

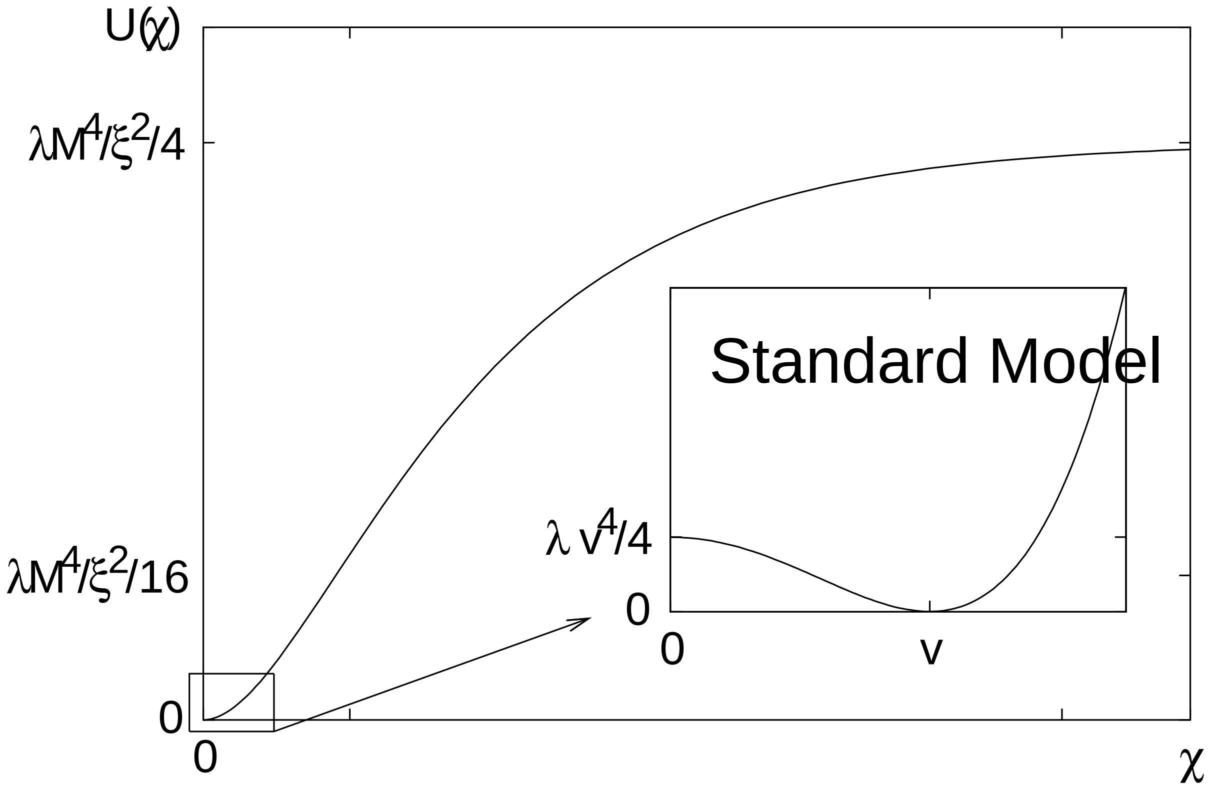
Consider large Higgs fields $h > M_P/\sqrt{\xi}$, which may have existed in the early Universe

The Higgs field not only gives particles their masses $\propto h$, but also determines the gravity interaction strength:

$M_P^{\text{eff}} = \sqrt{M_P^2 + \xi h^2} \propto h$

For $h > \frac{M_P}{\sqrt{\xi}}$ (classical) physics is the same (M_W/M_P^{eff} does not depend on h)!

Potential in Einstein frame



χ - canonically normalized scalar field in Einstein frame.

Potential for the Higgs field may be flat at large values of h: Linde chaotic inflation

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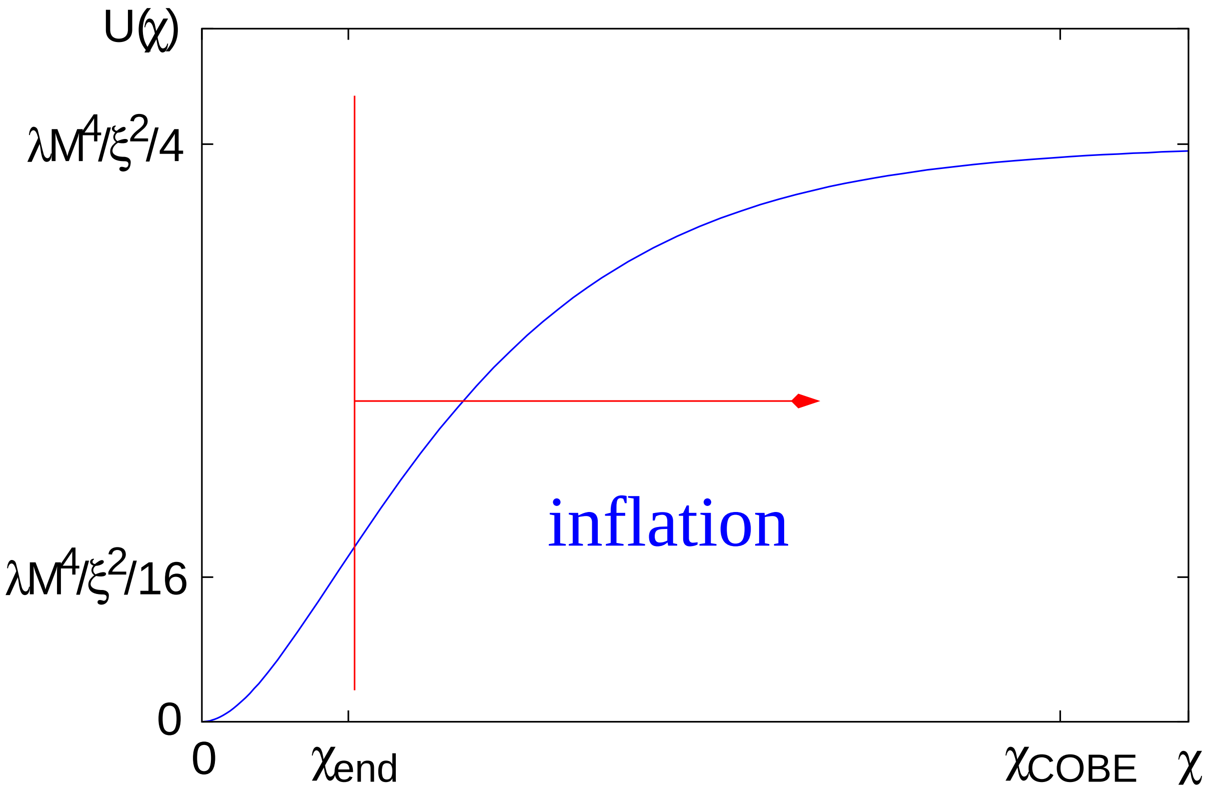
Inflation, Big Bang - all in the framework of the Standard Model

Stage 1: Higgs inflation, $h > \frac{M_P}{\sqrt{\xi}}$, slow roll of the Higgs field



- Makes the Universe flat, homogeneous and isotropic
- Produces fluctuations leading to structure formation: clusters of galaxies, etc

Slow roll stage

COBE normalization $U/\epsilon = (0.0276 M_P)^4$ gives

$$\xi \simeq \sqrt{\frac{\lambda}{3}\frac{N_{\rm COBE}}{0.027^2}} \simeq 47000\sqrt{\lambda} = 47000\frac{m_H}{\sqrt{2}v}$$

Connection of ξ and the Higgs mass!

Number of e-folds of inflation at the moment h_N is $N \simeq \frac{6}{8}\frac{h_N^2 - h_{\rm end}^2}{M_P^2/\xi}$

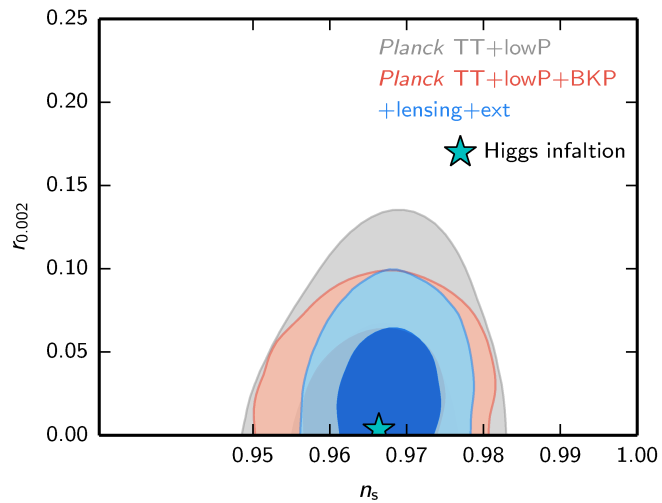
Slow roll ends at $\chi_{\rm end} \simeq M_P$; and "begins" at $\chi_{60} \simeq 5M_P$

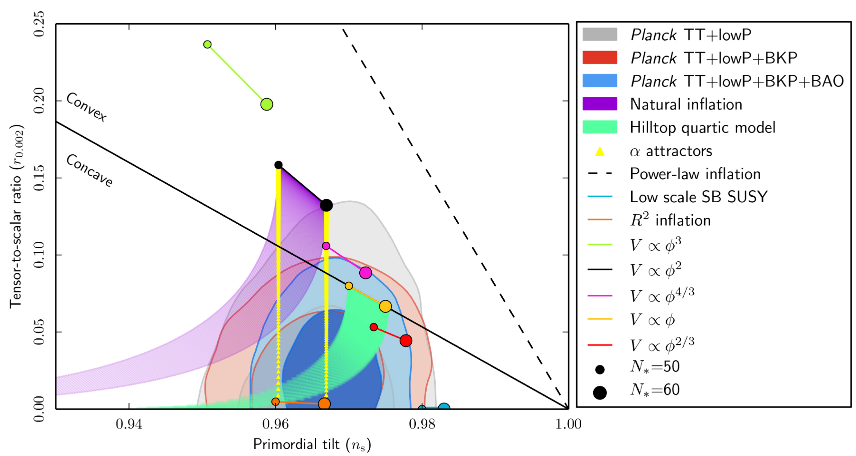
$$\epsilon = \frac{M_P^2}{2}\left(\frac{dU/d\chi}{U}\right)^2, \quad \eta = M_P^2\frac{d^2U/d\chi^2}{U}$$

$$n_s = 1 - 6\epsilon + 2\eta, \qquad r = 16\epsilon$$

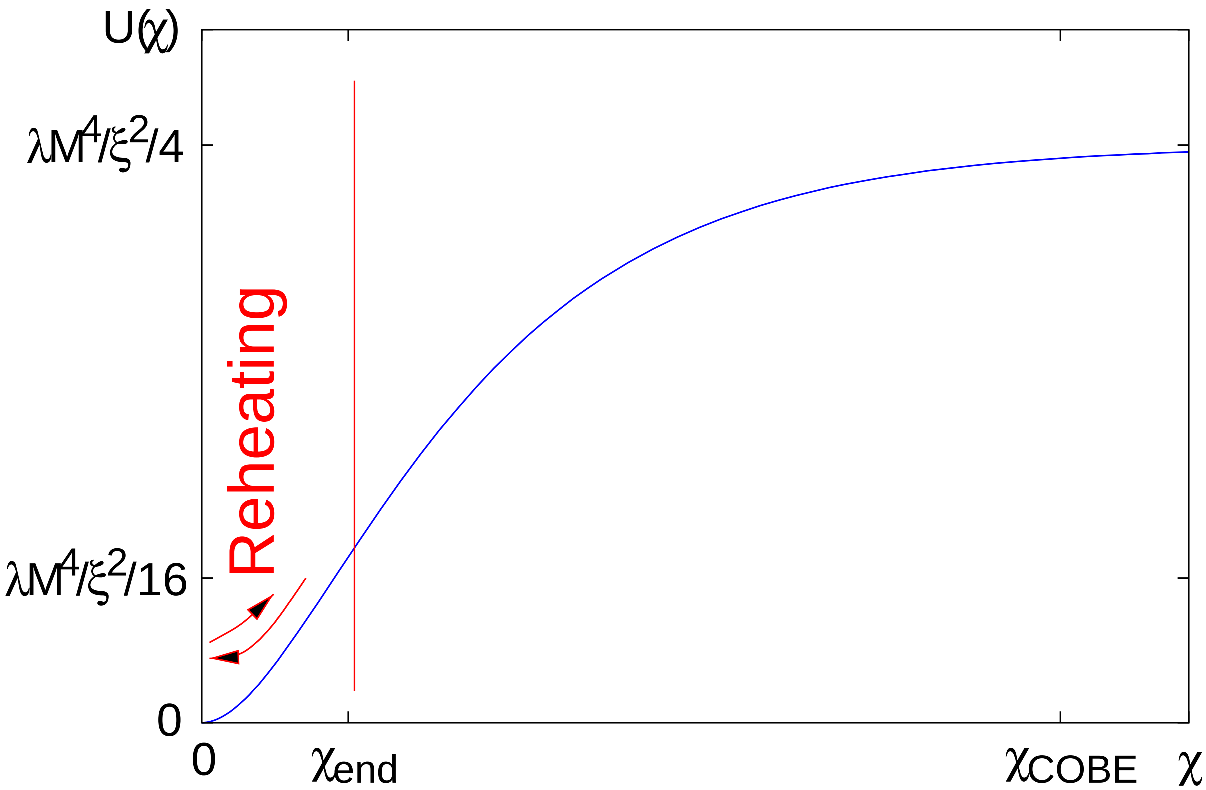
CMB parameters - spectrum and tensor modes, $\xi \gtrsim 1000$

$$n_s = 0.97, \quad r = 0.003$$





Stage 2: Big Bang, $\frac{M_P}{\xi} < h < \frac{M_P}{\sqrt{\xi}}$, Higgs field oscillations



- All particles of the Standard Model are produced
- Coherent Higgs field disappears
- The Universe is heated up to $T \propto M_P/\xi \sim 10^{14}$ GeV

Any theory of inflation is non-renormalisable, as it includes gravity!

How to account for this fact in general, and for the Higgs inflation in particular? Higher dimensional operators? Radiative corrections?

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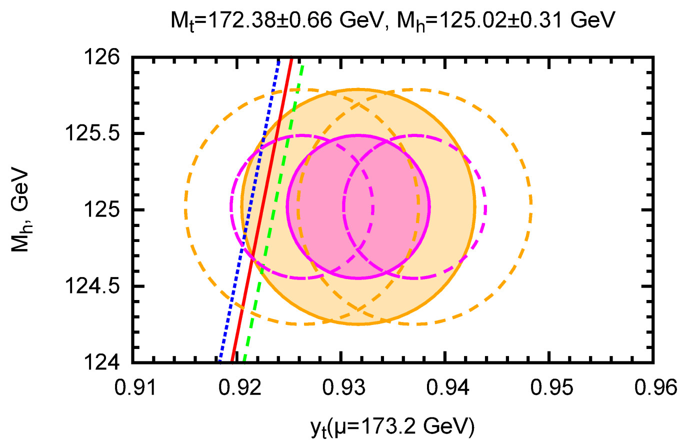
Radiative corrections, different approaches: Barvinsky, Kamenshchik, Starobinsky; Bezrukov, MS; De Simone, Hertzberg, Wilczek; George, Mooij, Postma,...

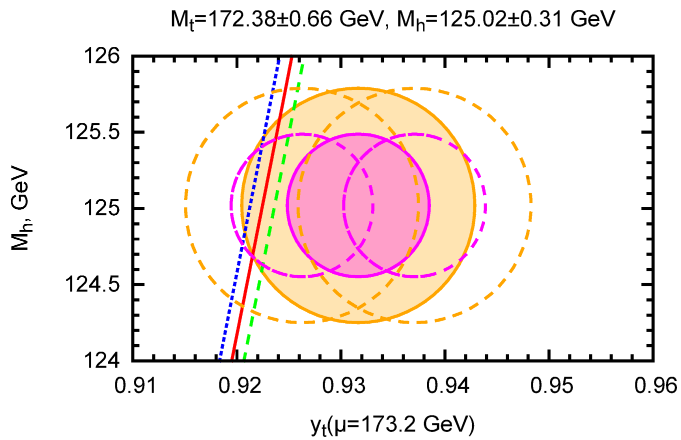
Higgs inflation: $y_t < y_t^{\text{crit}}$



The same story as the Higgs inflation at the tree level.

Critical Higgs inflation: $y_t \approx y_t^{\mathrm{crit}}$

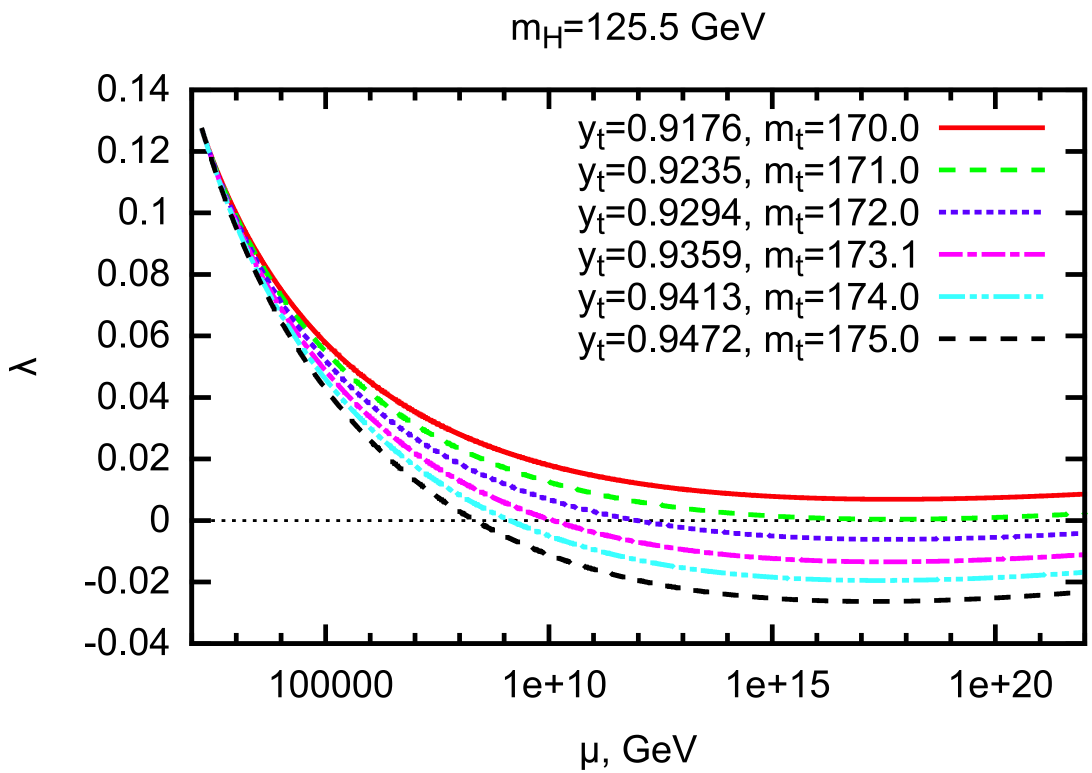
Extreme fine tuning of the Higgs and top quark masses



Bezrukov, MS

For y_t very close to y_t^{crit} : critical Higgs inflation - tensor-to-scalar ratio can be large, $\xi \sim 10$

Behaviour of λ:



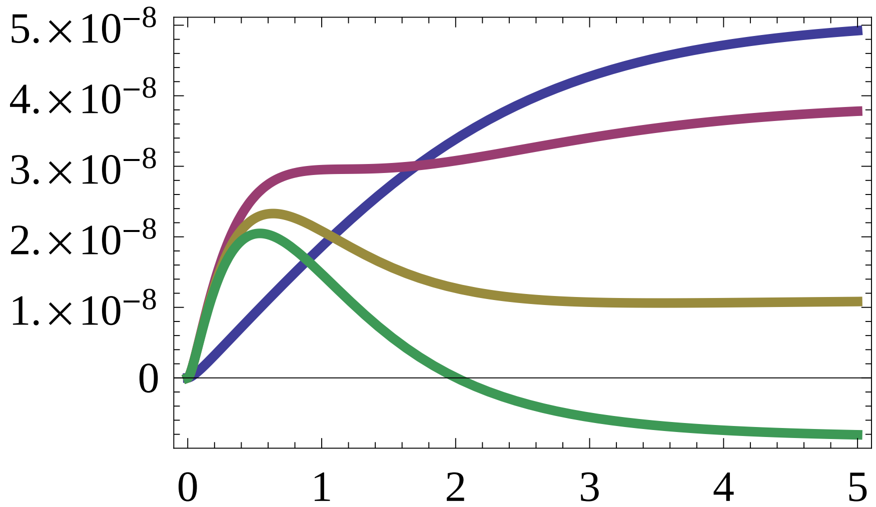
Effective potential

$$U(\chi) \simeq \frac{\lambda(z')}{4\xi^2}\bar{\mu}^4\,, \quad z' = \frac{\bar{\mu}}{\kappa M_P}, \quad \bar{\mu}^2 = M_P^2\left(1 - e^{-\frac{2\chi}{\sqrt{6}M_P}}\right)$$

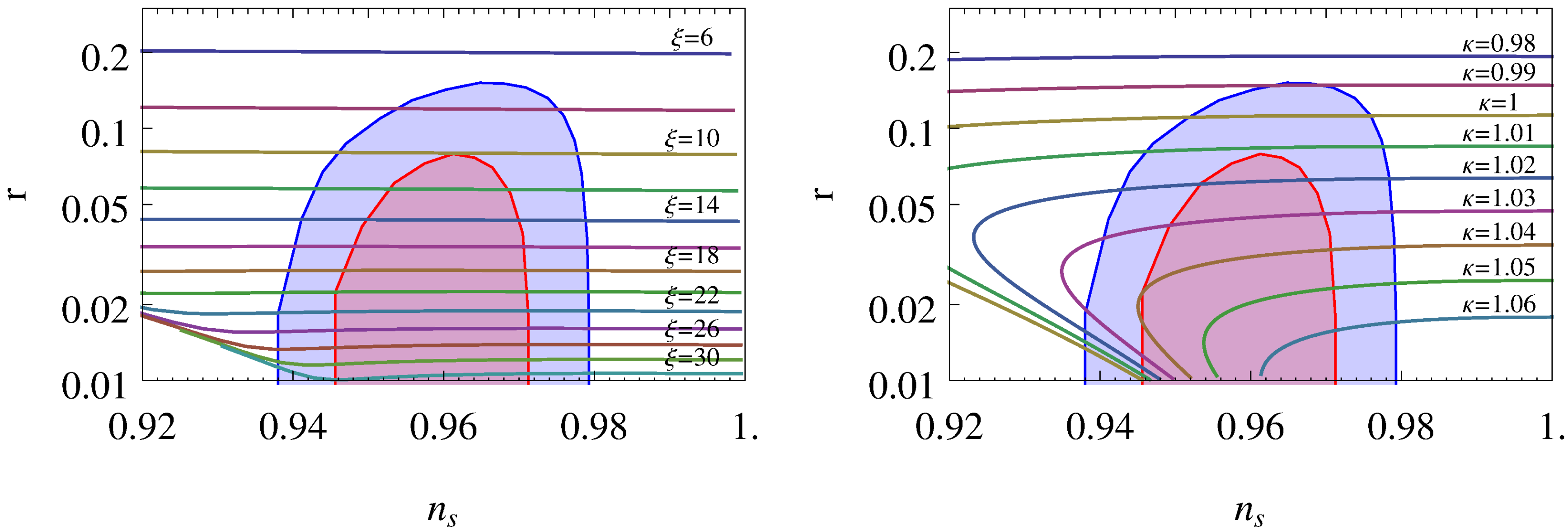
The parameter μ that optimises the convergence of the perturbation theory is related to $\bar{\mu}$ as

$$\mu^2 = \alpha^2 \frac{y_t(\mu)^2}{2}\frac{\bar{\mu}^2}{\xi(\mu)}\,, \quad \alpha \simeq 0.6$$

Behaviour of effective potential for $\lambda_0 \simeq b/16$:



The inflationary indexes

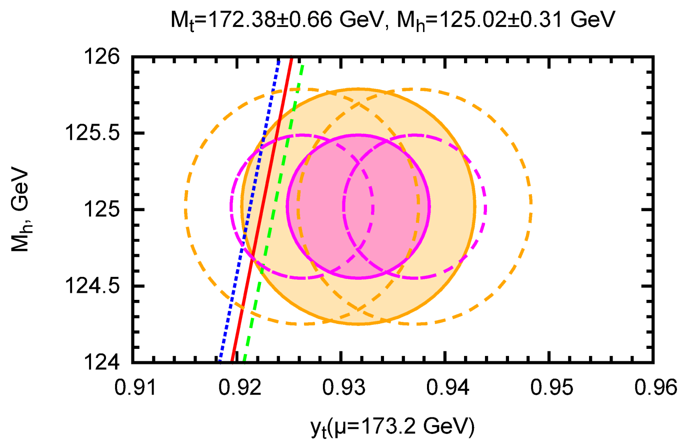


r can be large!

see also Hamada, Kawai, Oda and Park

Critical Higgs inflation only works if both Higgs and top quark masses are close to their experimental values.

Living beyond the edge: Higgs inflation and vacuum metastability, $y_t > y_t^{\mathrm{crit}}$



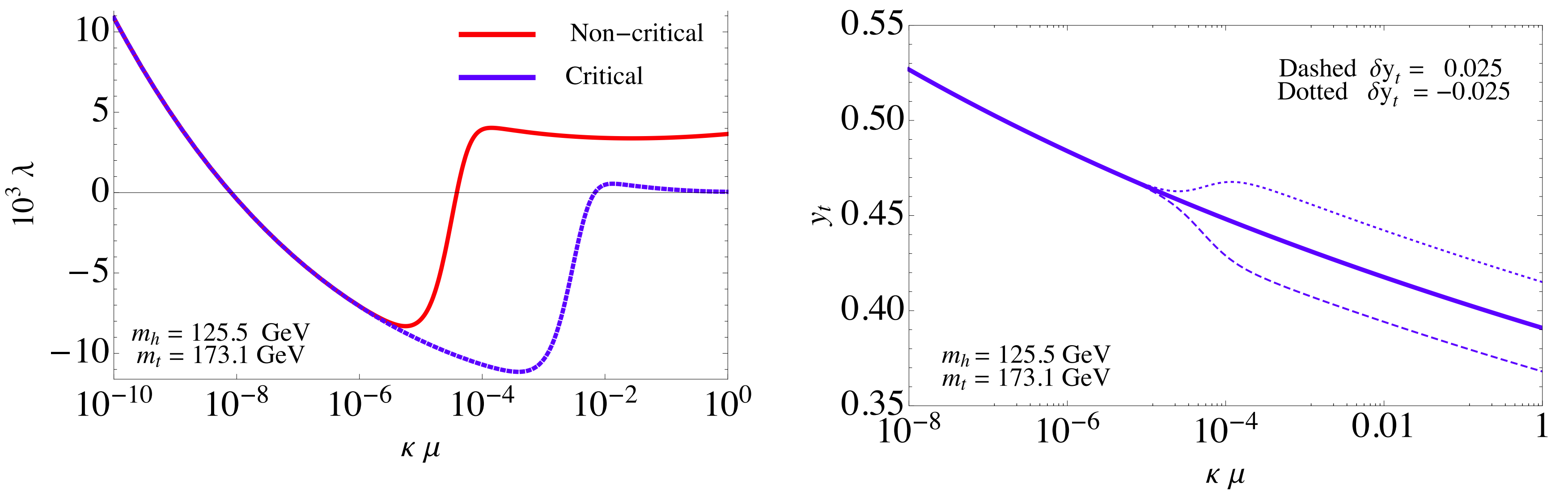
Bezrukov, Rubio, MS

Renormalisation of the SM coupling constants at the scale M_P/ξ:

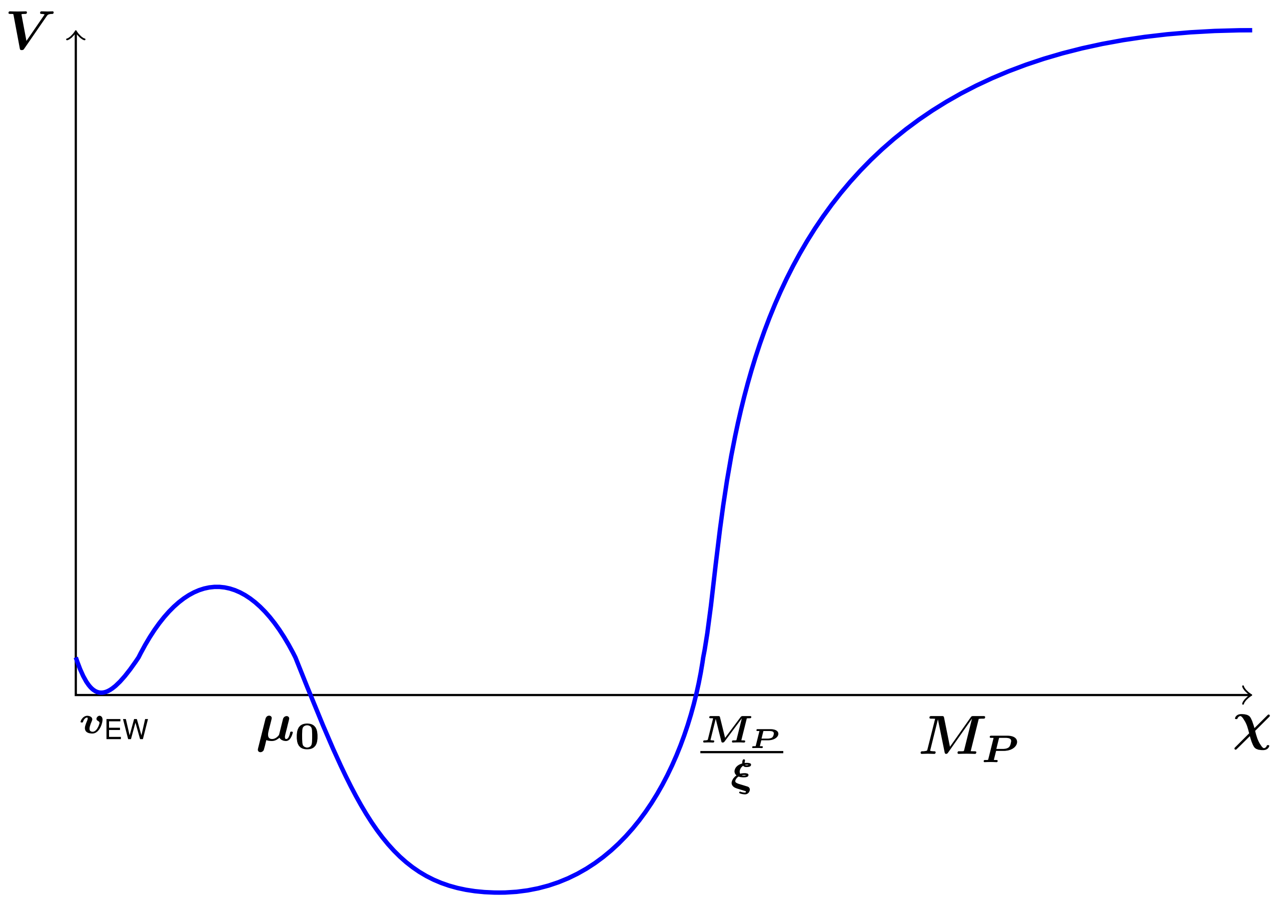
"jumps" of λ and y_t controlled by UV completion of the SM, which cannot be found from low-energy observables of the SM

Bezrukov, Magnin, MS., Sibiryakov

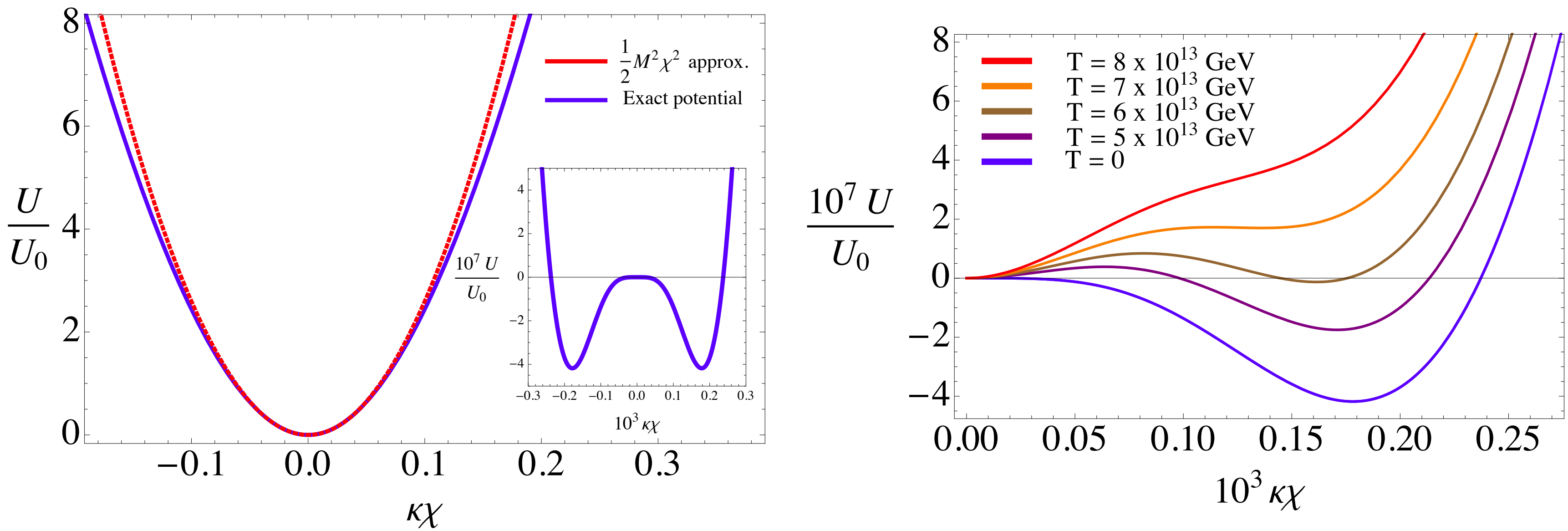
$\lambda(M_P/\xi)$ is small due to cancellations between fermionic and bosonic loops: $\delta\lambda$ can be of the order of λ



Higgs potential



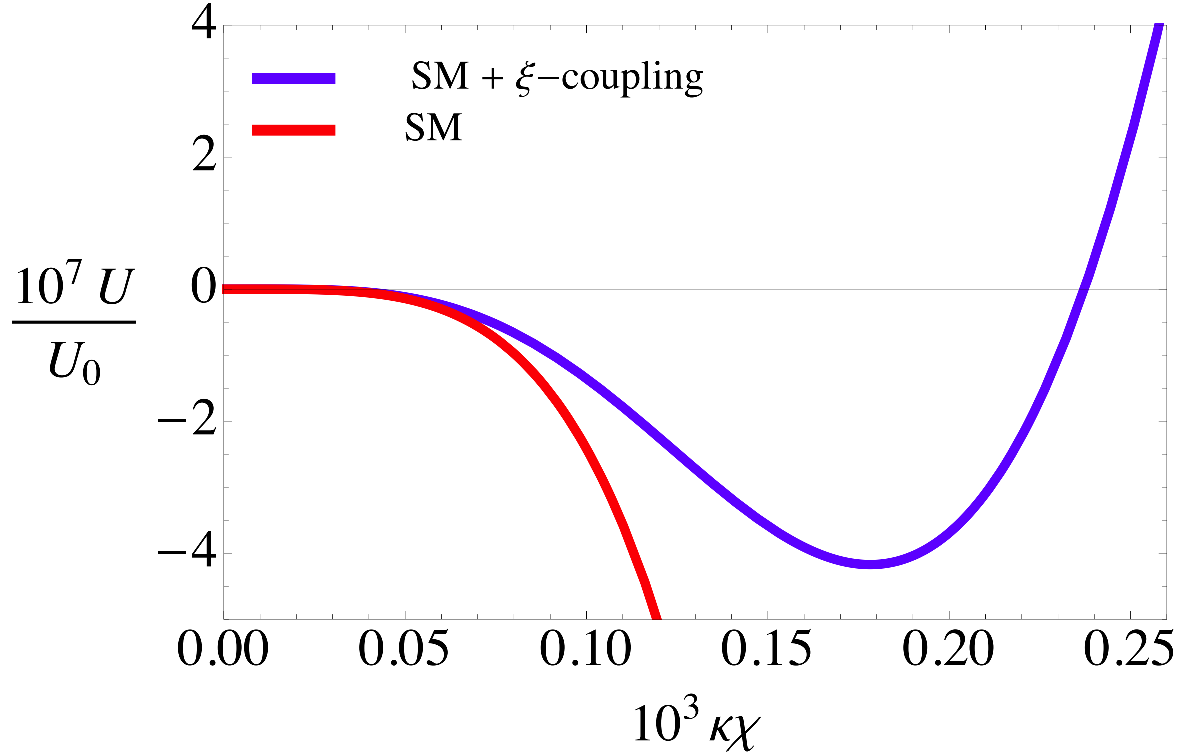
Symmetry restoration



Reheating temperature $T_R \simeq 2 \times 10^{14}$ GeV $> T_+ \simeq 7 \times 10^{13}$ GeV, $T_c = 6 \times 10^{13}$ GeV

(Meta) stability of false vacuum

Computation for SM: Espinosa, Giudice, Riotto



Predictions for critical indexes n_s and r are the same as for non-crtitical Higgs inflation

$$n_s = 0.97, \;\; r = 0.003$$

Critical Higgs inflation at $y_t > y_t^{\rm crit}$?

Critical Higgs inflation : small $\xi \sim 10$ - the depth of the large Higgs value vacuum is comparable with the energy stored in the Higgs after inflation: the required reheating temperature is too large, $T_+ \simeq 10^{16}$ GeV and cannot be achieved.

Conclusions, Lecture 2

- Higgs boson of the Standard Model can make the universe flat, homogeneous and isotropic, and can lead to primordial perturbations needed for structure formation
- The Higgs inflation can take place both for absolutely stable and metastable vacuum, with universal predictions $n_s = 0.97, \;\; r = 0.003$ for a wide range of parameters
- For critical Higgs inflation corresponding to $y_t \approx y_t^{\mathrm{crit}}$ $\;\; n_s$ and r can be substantially different from these values