ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

What can we learn from cosmology for particle physics?

Mikhail Shaposhnikov

SSP 2012, Groningen, 21 June 2012

Outline

- Particle physics-cosmology interplay
- LHC and cosmology
- What kind of new physics we may expect?
- Conclusions

Particle physics-cosmology interplay

Interplay between particle physics (distances $l < 10^{-14}$ cm)

and

cosmology (distances $l > 10^{25}$ cm)

What is the relation?

Universe expands $\Longrightarrow$

it was very hot and dense in the past $\Longrightarrow$

interactions between elementary particles were essential $\Longrightarrow$

they determined the structure of the Universe we see today

- Structure of the Universe $\Longrightarrow$ structure of particle theory
- Particle theory $\Longrightarrow$ structure of the Universe

Interaction between astronomy and particle physics started long time ago...

1675:

Ole Roemer estimated the speed of light from delay of the Jupiter satellite eclipse

1686:

Newton found the gravity constant (only in 1798 Cavendish measured it in the lab)

G_N and c are important parameters of particle physics!

New era started in 1965 with discovery by Penzias and Wilson of cosmic microwave background radiation, confirming thus the Big Bang theory of Lemaitre and Gamov, following from Fridman expansion


Disclaimer: cosmology cannot be used to prove some particular particle physics model. It can be used rather as a tool for rejecting particle physics theories.

Zeldovich: Universe is a poor man accelerator: it can produce very heavy particles, and it can produce very weakly interacting particles, since the temperature and particle number densities were high in the past. Unfortunately, the experiment happened just once!

Particle physics, dark matter, and baryon asymmetry of the Universe

What is the nature of dark non-baryonic matter? New stable or long-lived particle?

Why the Universe contains more matter than antimatter? The particle theory theory must violate baryon number and break C and CP symmetries.

LHC and cosmology

Suppose that the LHC discovers the Higgs boson with the mass $M_H = M_{min}$, finds no new particles, and continue to confirm the Standard Model

$$M_{\rm min} = \left[129 + \frac{M_t - 172.9\,{\rm GeV}}{1.1\,{\rm GeV}} \times 2.2 - \frac{\alpha_s - 0.1184}{0.0007} \times 0.56\right] {\rm GeV}.$$

with theoretical uncertainties of $\pm\,(1-2)$ GeV,

$$M_{\rm min} = 129 \pm 6\,{\rm GeV}$$

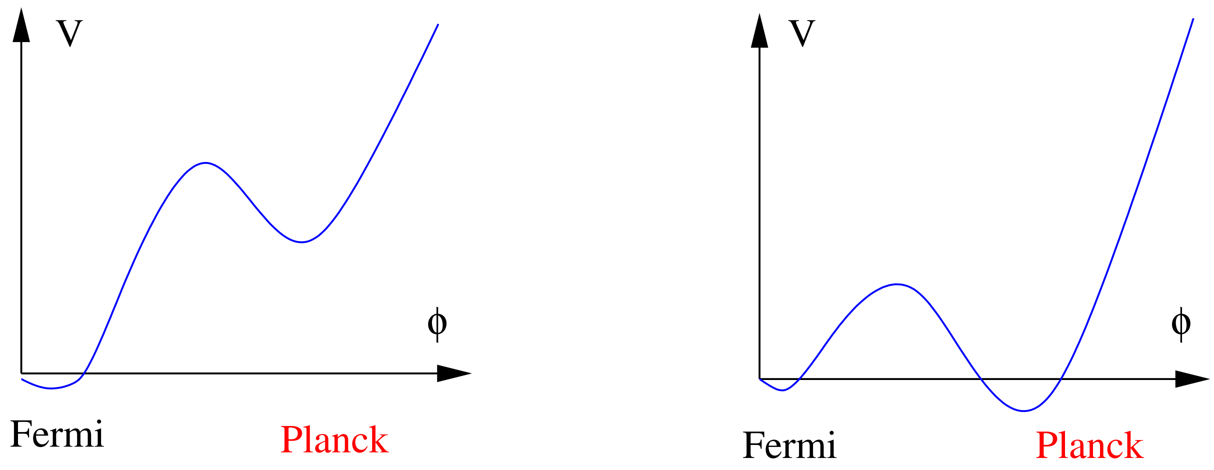
if experimental uncertainties for m_t and α_s are taken at 2σ level.

What this would mean for cosmology?

Physical significance of M_{min} (I)

Krasnikov '78, Hung '79; Politzer and S. Wolfram '79; G. Altarelli and G. Isidori '94; J. A. Casas, J. R. Espinosa and M. Quiros '94,'96; ...

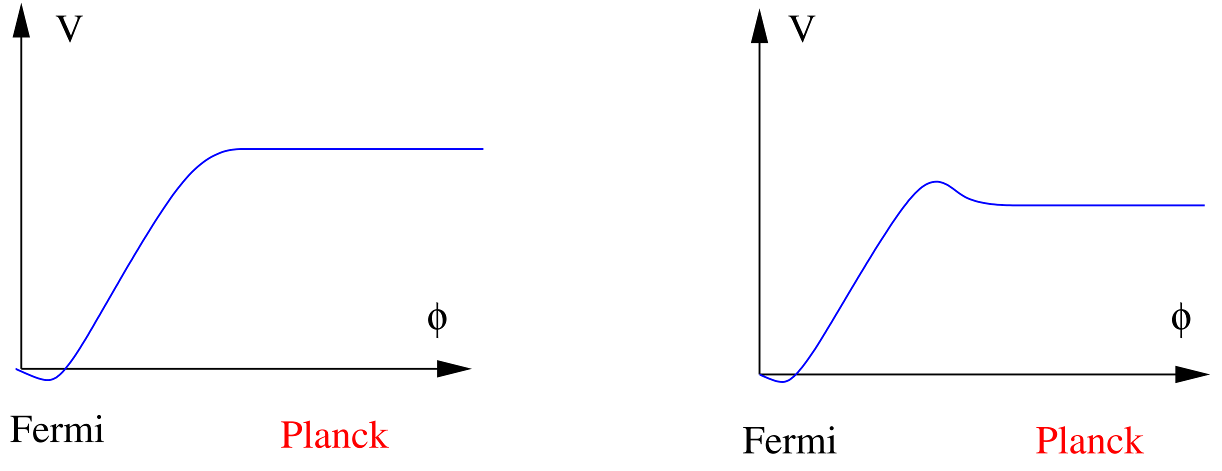
If $m_H < M_{min}$, there is a deeper vacuum with the Higgs vacuum expectation value below the Planck mass, and the Standard Model vacuum is metastable (but lives longer than the Universe lifetime, if $M_H > 111$ GeV Espinosa et al.). SM is a valid effective field theory all the way up to the Planck scale!



Physical significance of M_{min} (II)

Bezrukov, M.S.; De Simone, Hertzberg, Wilczek

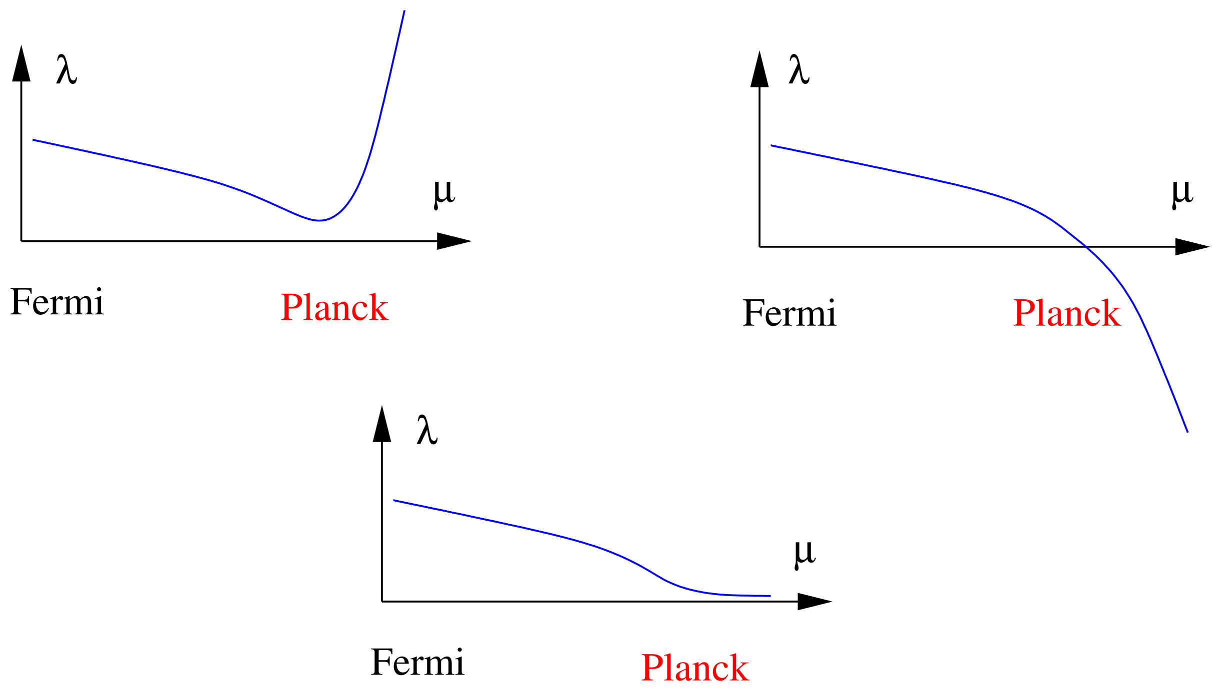
If $m_H > M_{min}$, the Higgs boson of the Standard Model can play the role of the inflaton and can make the Universe flat, homogeneous and isotropic, produce the hot Big Bang, and generate the spectrum of primordial fluctuations, necessary for structure formation.



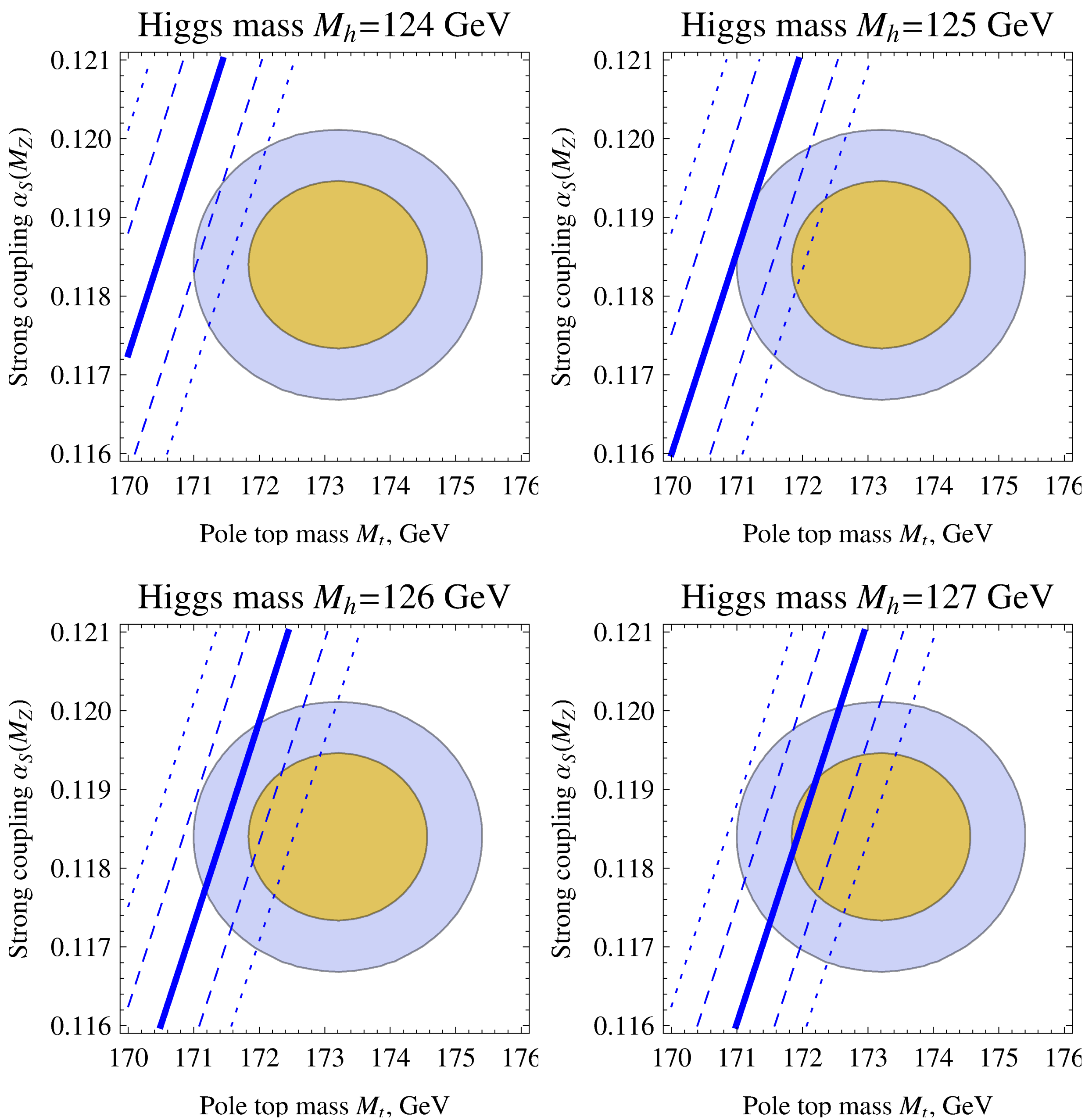
Physical significance of M_{min} (III)

M.S., Wetterich

The gravity and the Standard Model can be asymptotically safe (valid at all energies) only when $m_H = M_{min}$ (assuming positive gravity contribution to the running scalar self-coupling, found in exact RG analysis)



Bezrukov, Kalmykov, Kniehl, MS Comparison with the LHC evidence:



Dark matter

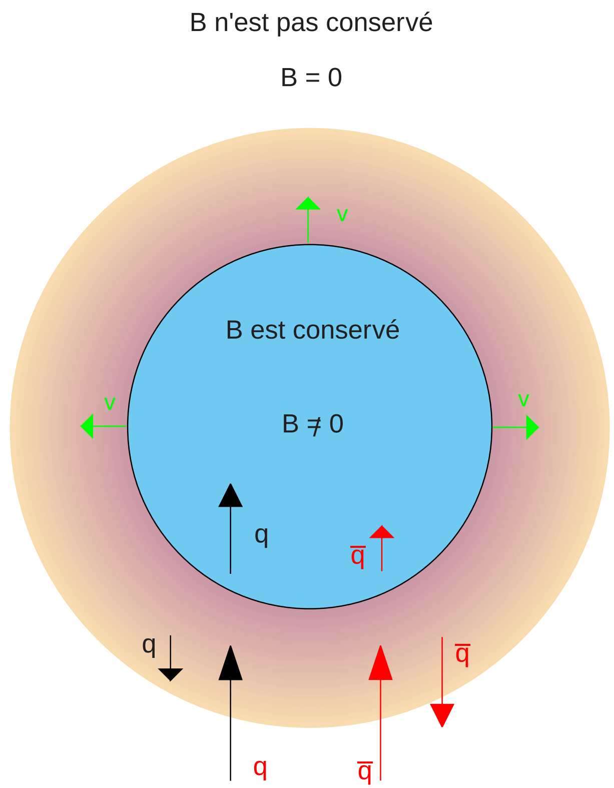
Most popular DM candidate: WIMP, associated with new physics solving the hierarchy problem at the electroweak scale. If no new physics is discovered at the LHC, this candidate is not that attractive anymore...

What is the Dark matter particle?

Baryon asymmetry of the Universe I

Popular mechanism for baryogenesis:

- Electroweak baryogenesis. Idea (Cohen Kaplan, Nelson): at high temperatures we are in the symmetric phase of the EW theory. During the universe cooling the first order EW phase transition (PT) goes through nucleation of bubbles of the new (Higgs) phase. Scattering of different particles on the domain walls leads to separation of baryon number and due to sphalerons to baryon asymmetry.



Does not work in the SM - no electroweak PT. Does not work in the MSSM: light stop is required for first order PT, excluded by the LHC.

However, may well work in other models - no theorem can be proven!

Baryon asymmetry of the Universe II

Another popular mechanism for baryogenesis:

- Thermal leptogenesis. Idea (Yanagida, Yoshimura): superheavy Majorana leptons with the mass $\sim 10^{10}$ GeV decay and produce lepton asymmetry, which is converted to baryon asymmetry by sphalerons.

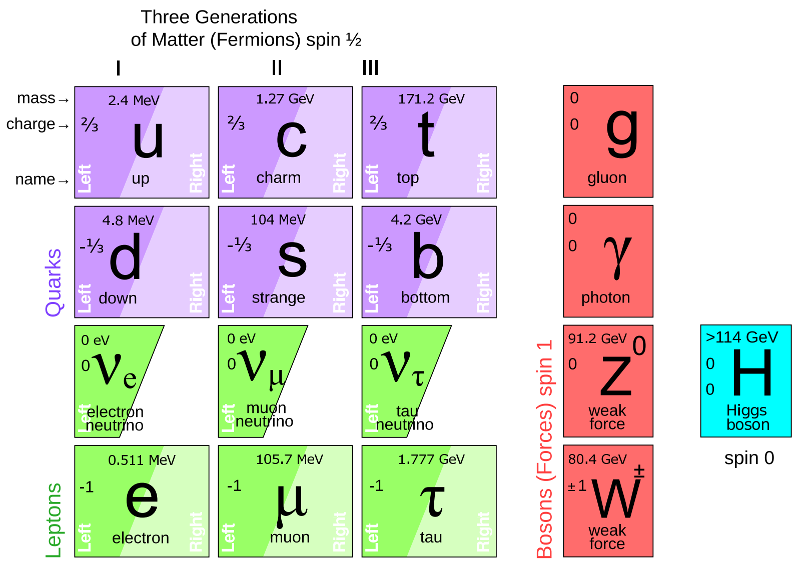
Necessity of heavy particles $\Longrightarrow$ large radiative corrections to the Higgs mass (hierarchy problem) $\Longrightarrow$ SUSY at the electroweak scale. But, according to our assumption, it is not found at the LHC...

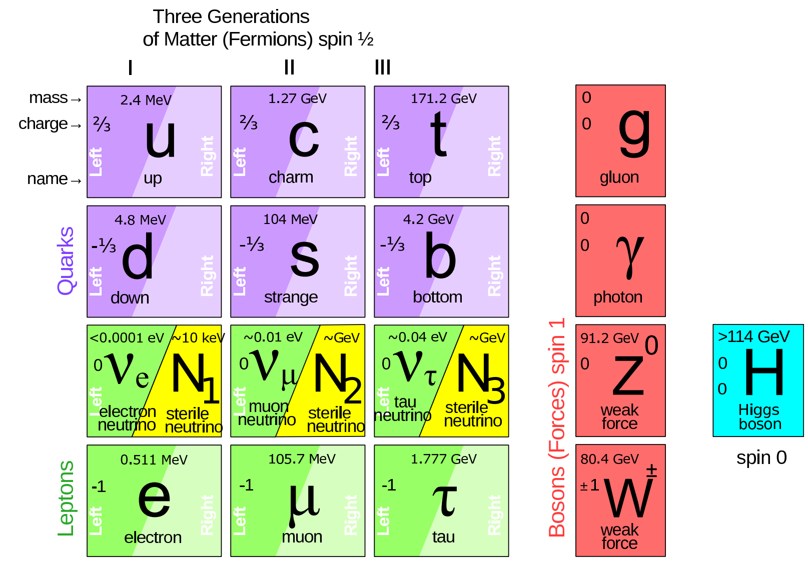
Thermal leptogenesis cannot be disproved, but will be fine tuned...

So, if the LHC will confirm the SM, and see nothing else, popular mechanisms for baryogenesis will be disfavored.

How the baryon asymmetry of the Universe has emerged?

What kind of new physics we may expect?





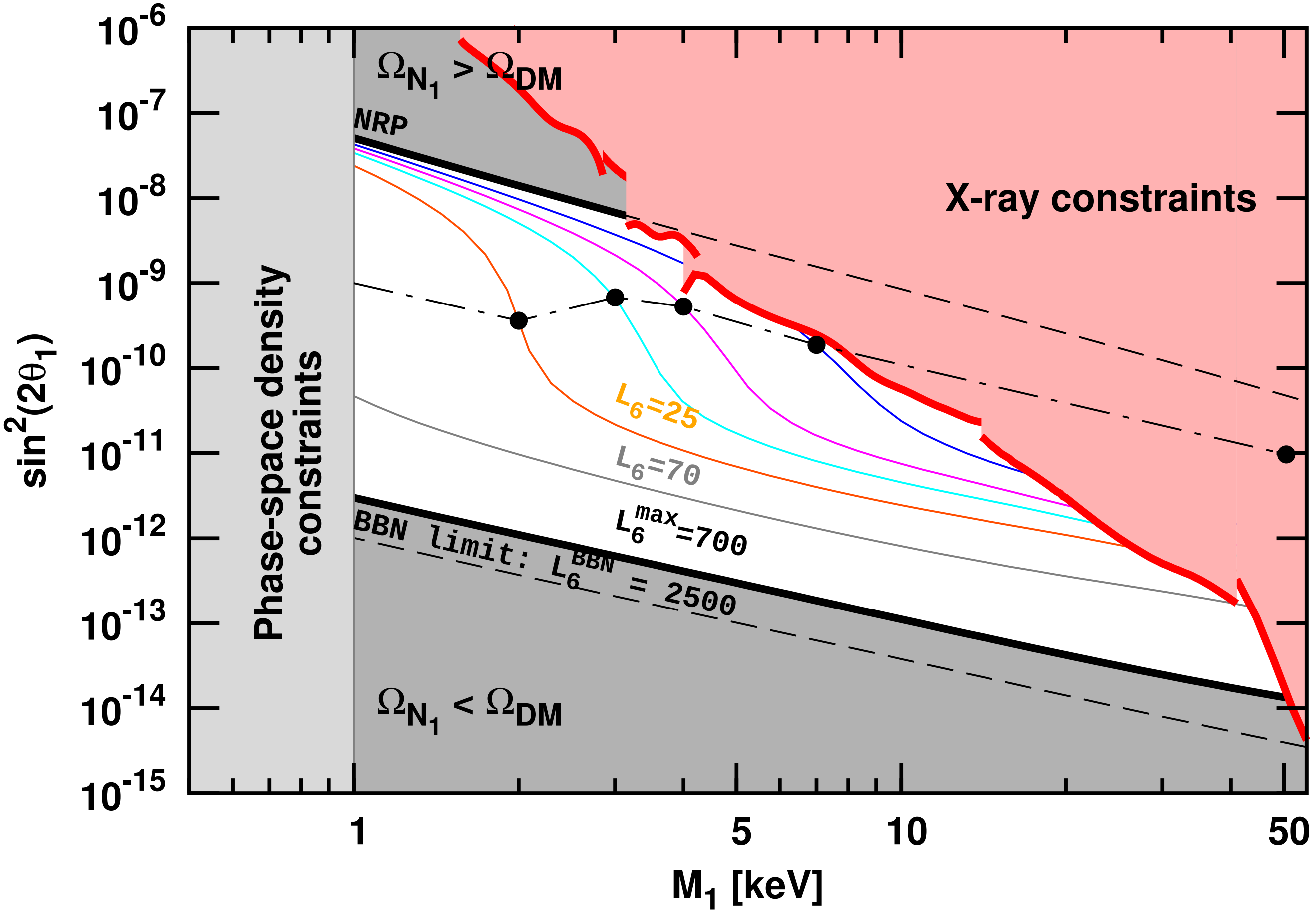
Role of N_e with mass in keV region: dark matter

Role of $N_\mu,\ N_\tau$ with mass in 100 MeV – GeV region: “give” masses to neutrinos and produce baryon asymmetry of the Universe

Role of the Higgs: give masses to quarks, leptons, Z and W and inflate the Universe.

Constraints on DM sterile neutrino N_1

- Stability. N_1 must have a lifetime larger than that of the Universe
- Production. N_1 are created in the early Universe in reactions $l\bar{l} \to \nu N_1, \;\; q\bar{q} \to \nu N_1$ etc. We should get correct DM abundance
- Structure formation. If N_1 is too light it may have considerable free streaming length and erase fluctuations on small scales. This can be checked by the study of Lyman-α forest spectra of distant quasars and structure of dwarf galaxies
- X-rays. N_1 decays radiatively, $N_1 \to \gamma\nu$, producing a narrow line which can be detected by X-ray telescopes (such as Chandra or XMM-Newton). This line has not been seen yet



Important: DM sterile neutrino production requires the presence of large, $\Delta L/L > 2 \times 10^{-3}$ lepton asymmetry at temperature $T \sim 100$ MeV. It can only be produced in the νMSM.

How to find DM sterile neutrino?

Boyarsky et al: Flux from DM decay $N_1 \to \nu\gamma$:

$$F_{\rm dm} = \frac{\Gamma_{\rm rad} M_{\rm dm}^{\rm fov}}{8\pi D_L^2} \approx \frac{\Gamma_{\rm rad}\Omega_{\rm fov}}{8\pi} I, \quad I = \int_{\text{line of sight}} \rho_{\rm dm}(r)dr$$

(Valid for small redshifts $z \ll 1$, and small fields of view $\Omega_{\rm fov} \ll 1$)
Strategy: Use X-ray telescopes (such as Chandra and XMM Newton) to look for a narrow γ line against astrophysical background. Choose astrophysical objects for which:

- The value of line of sight DM density integral I is maximal
- The X-ray background is minimal

$\Longrightarrow$ Look at Milky Way and dwarf satellite galaxies !

Prediction: active neutrino masses

Asaka, Blanchet, M.S: The minimal number of sterile neutrinos, which can explain the dark matter in the Universe and neutrino oscillations, is $\mathcal{N} = 3$. Only one sterile neutrino can be the dark matter. Lightest active neutrino:

$$m_1 \leq 2 \cdot 10^{-3} \text{ eV}.$$

Normal hierarchy:

$m_2 = [9.05^{+0.2}_{-0.1}] \cdot 10^{-3}\text{eV} \simeq \sqrt{\Delta m^2_{solar}}$,

$m_3 = [4.8^{+0.6}_{-0.5}] \cdot 10^{-2}\text{eV} \simeq \sqrt{\Delta m^2_{atm}}$,

Inverted hierarchy: $m_{2,3} = [4.7^{+0.6}_{-0.5}] \cdot 10^{-2}$ eV .

Prediction: neutrinoless double β decay

F. Bezrukov: Effective Majorana mass $m_{\beta\beta}$

Normal hierarchy: $1.3\ \mathrm{meV} < m_{\beta\beta} < 3.4\ \mathrm{meV}$

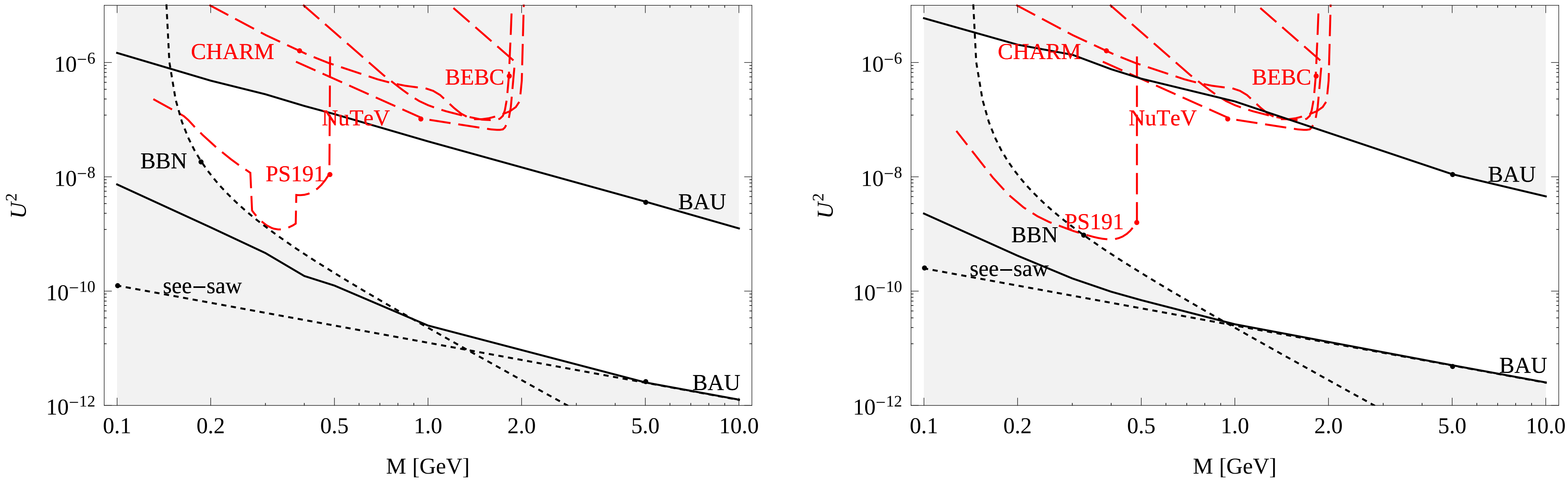
Inverted hierarchy: $13\ \mathrm{meV} < m_{\beta\beta} < 50\ \mathrm{meV}$

Knowing $m_{\beta\beta}$ experimentally will allow to fix Majorana CP-violating phases in neutrino mass matrix, provided θ_{13} and Dirac phase δ are known.

Constraints on BAU sterile neutrinos $N_{2,3}$

Baryon asymmetry generation: CP-violation in neutrino sector+singlet fermion oscillations+sphalerons

- BAU generation requires out of equilibrium: mixing angle of $\boldsymbol{N_{2,3}}$ to active neutrinos cannot be too large
- Neutrino masses. Mixing angle of $\boldsymbol{N_{2,3}}$ to active neutrinos cannot be too small
- BBN. Decays of $\boldsymbol{N_{2,3}}$ must not spoil Big Bang Nucleosynthesis
- Experiment. $\boldsymbol{N_{2,3}}$ have not been seen yet



Constraints on U^2 coming from the baryon asymmetry of the Universe (solid lines), from the see-saw formula (dotted line) and from the big bang nucleosynthesis (dotted line). Experimental searched regions are in red - dashed lines. Left panel - normal hierarchy, right panel - inverted hierarchy. Gorbunov, M.S., Canetti

Experimental signatures - 1

Challenge - from baryon asymmetry: $U^2 \lesssim 5 \times 10^{-7} \left(\frac{\mathrm{GeV}}{M}\right)$

- Peak from 2-body decay and missing energy signal from 3-body decays of K, D and B mesons (sensitivity U^2)

  Example:

$$K^+ \to \mu^+ N, \quad M_N^2 = (p_K - p_\mu)^2 \neq 0$$

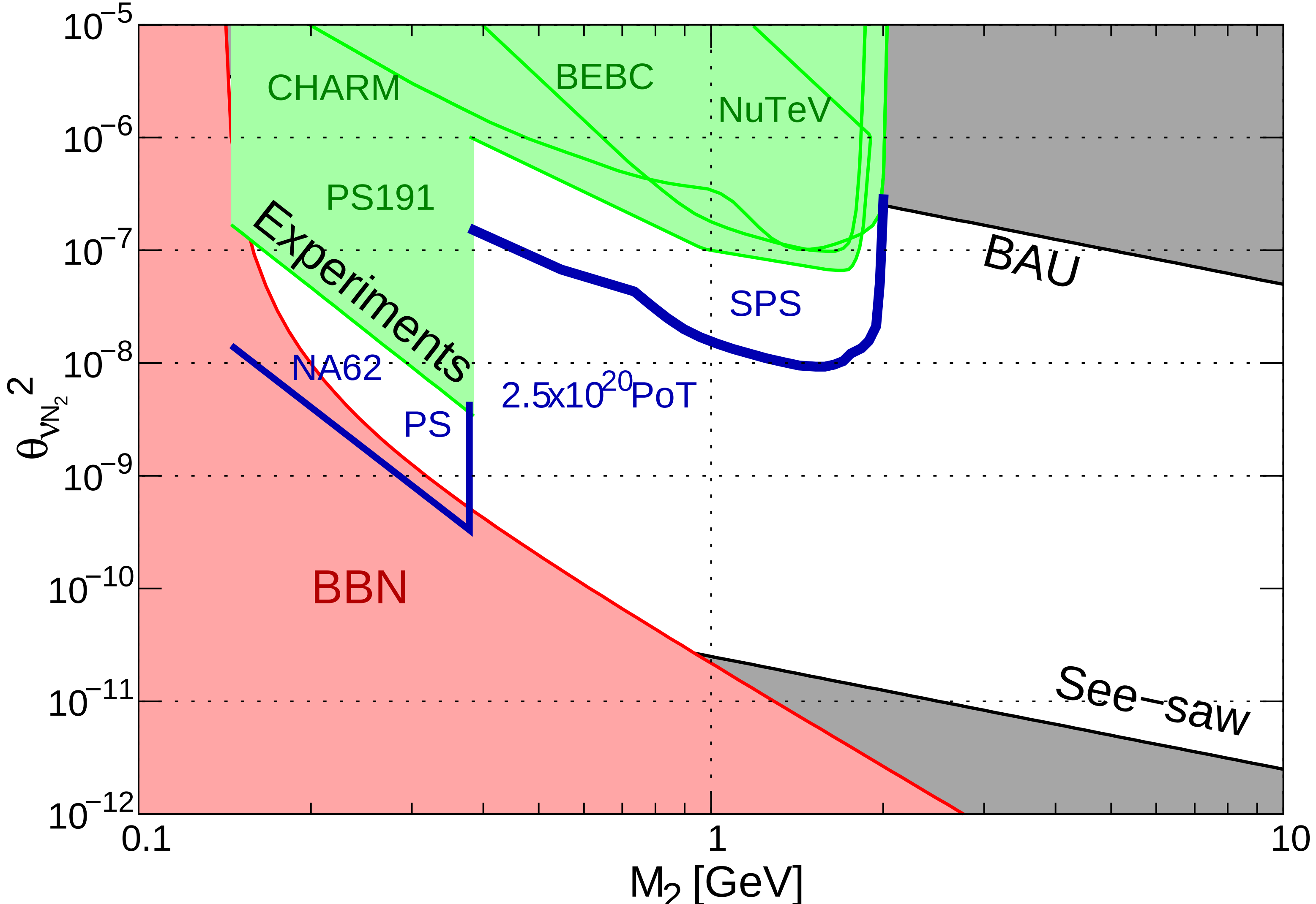
  Similar for charm and beauty.

  - $M_N < M_K$: NA62
  - $M_K < M_N < M_D$: charm and τ factories
  - $M_N < M_B$: B-factories (planned luminosity is not enough to get into cosmologically interesting region)

Experimental signatures - 2

- Two charged tracks from a common vertex, decay processes $N \to \mu^+\mu^-\nu$, etc. (sensitivity $U^4 = U^2 \times U^2$)
  First step: proton beam dump, creation of N in decays of $K,\ D$ or B mesons: U^2
  Second step: search for decays of N in a near detector, to collect all Ns: U^2
  - $M_N < M_K$: Any intense source of K-mesons (e.g. from proton targets of PS.)
  - $M_N < M_D$: Best option: SPS beam + near detector
  - $M_N < M_B$: Project X (?) + near detector
  - $M_N > M_B$: extremely difficult

CERN SPS is the best existing machine to uncover new physics below the electroweak scale. Sensitivity is proportional to total delivered protons on target.



Conclusions

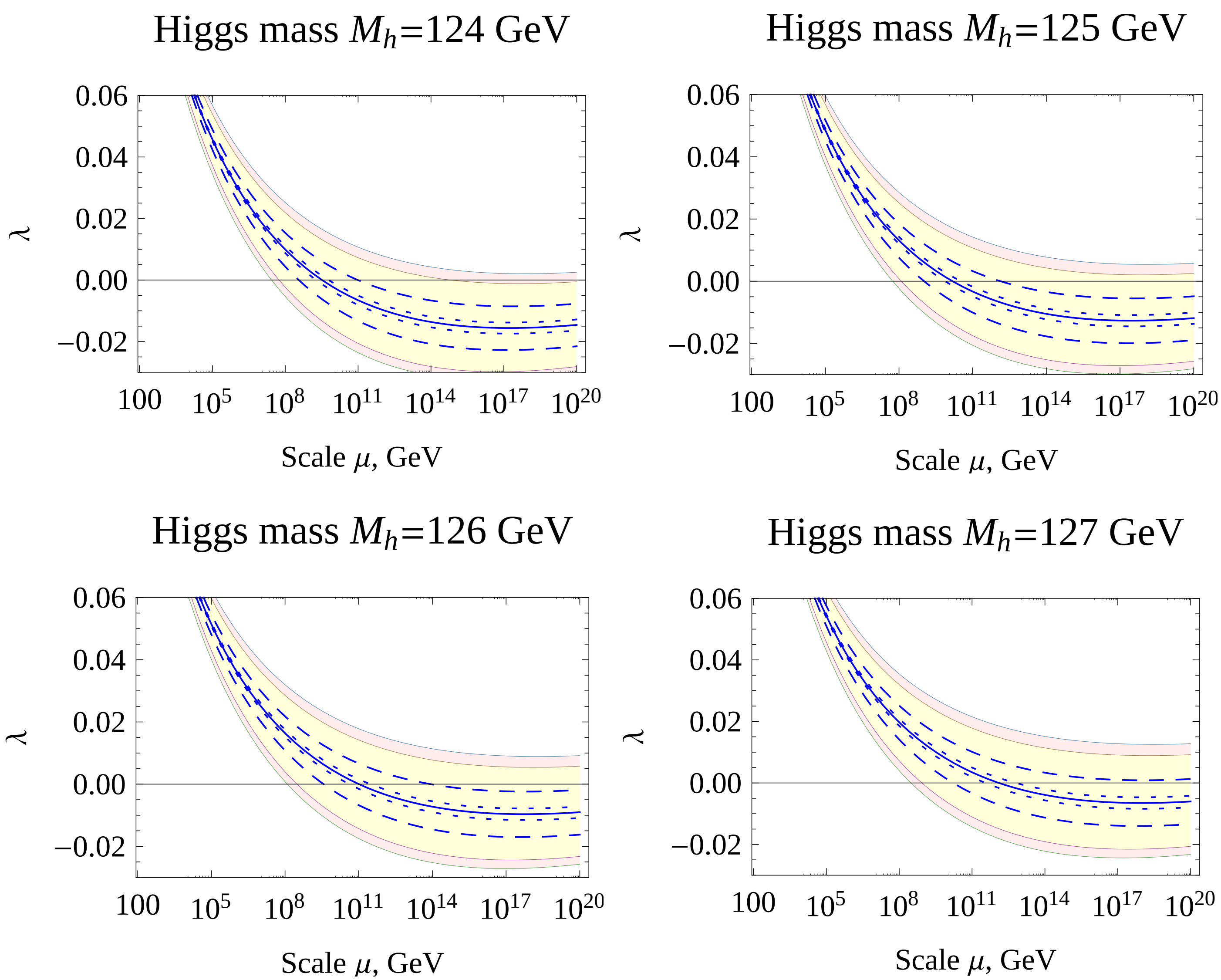
- At present, the only evidence for new physics comes from cosmology (dark matter, baryon asymmetry, inflation, dark energy) and neutrinos
- If this continues to be the case with the LHC experiments in coming years, it may indicate that new physics, responsible for neutrino masses and mixings, for dark matter, inflation and for baryon asymmetry of the universe may hide itself below the EW scale.
- New dedicated experiments in particle physics and cosmology are needed to uncover this physics
- Dark Matter - search for X-ray line from decays of DM particle
- Baryon asymmetry - search for Majorana leptons responsible for BAU and neutrino masses.

Back up slides

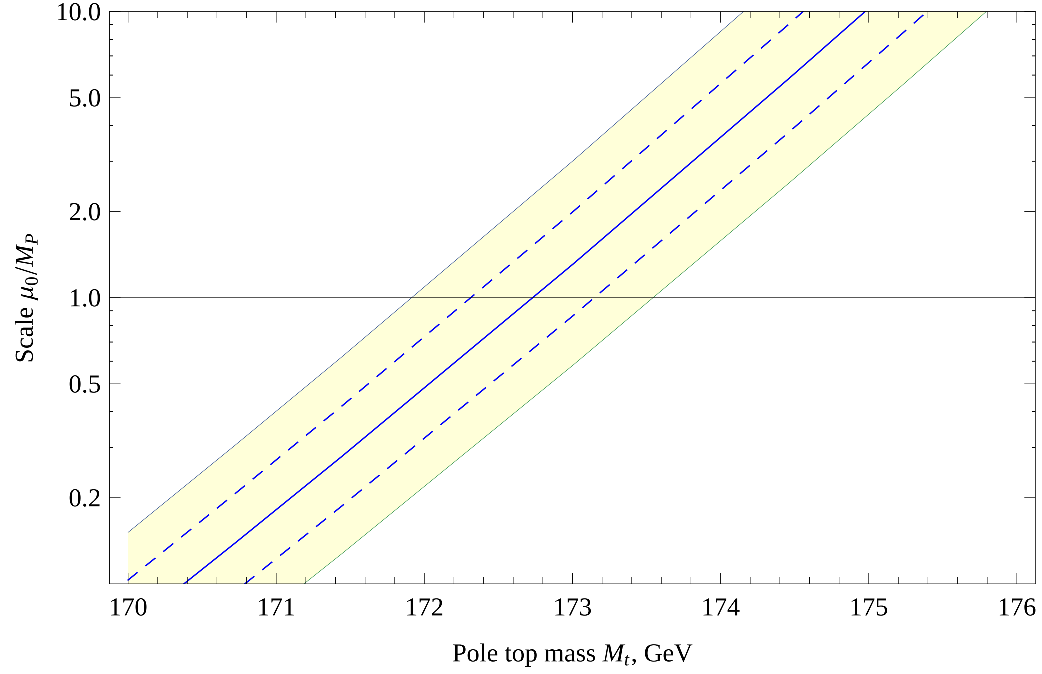
To decrease uncertainty: (the LHC accuracy can be as small as $\mathbf{200}$ MeV!)

- Compute two-loop $\mathcal{O}(\alpha^2)$ corrections to pole - $\overline{\mathrm{M}S}$ matching for the Higgs mass and top masses.
- If done, the theoretical uncertainty can be reduced to $\sim \mathbf{0.5-1}$ GeV, due to irremovable non-perturbative contribution $\sim \Lambda_{QCD}$ to top quark mass.
- Measure better t-quark mass (present error in m_H due to this uncertainty is $\simeq 4$ GeV at 2σ level): construct t-quark factory – e^+e^- or $\mu^+\mu^-$ linear collider with energy $\simeq \mathbf{200} \times \mathbf{200}$ GeV - proposal for the European high energy strategy committee
- Measure better α_s (present error in m_H due to this uncertainty is $\simeq 1$ GeV at 2σ level)

Behaviour of the Higgs self-coupling



Scale from equations: $\lambda(\mu_0) = 0$ and $\beta_\lambda^{\mathrm{SM}}(\mu_0) = 0$



μ_0 determined by the EW physics gives the Planck scale!

Numerical coincidence?

Fermi scale is determined by the Planck scale (or vice versa)?

Possible explanation - asymptotic safety of the SM+gravity