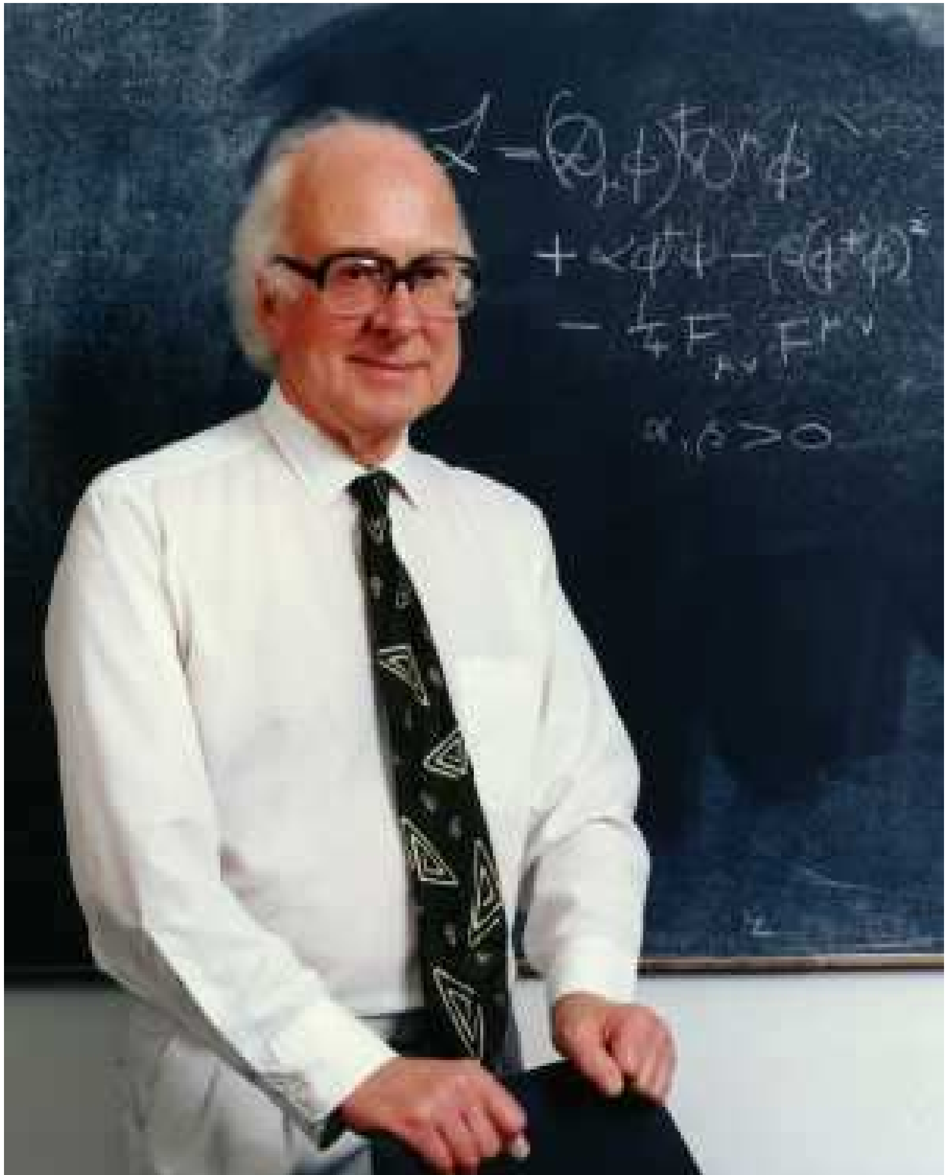
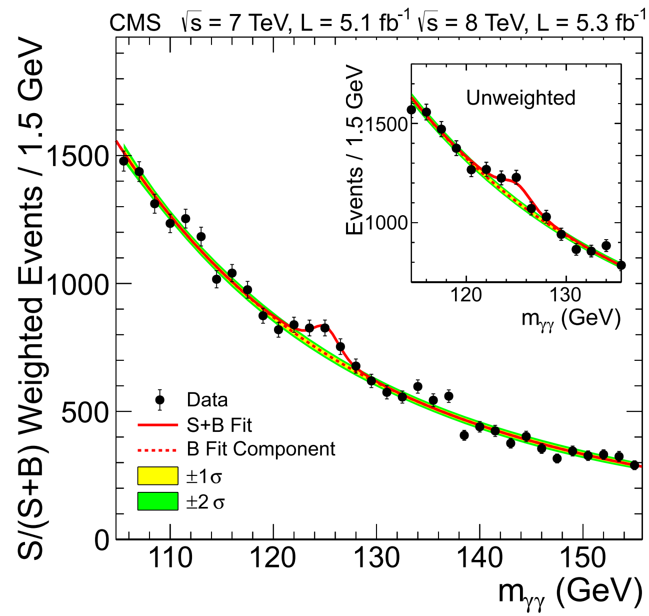
The University of Edinburgh
School of Physics & Astronomy



The Higgs Symposium

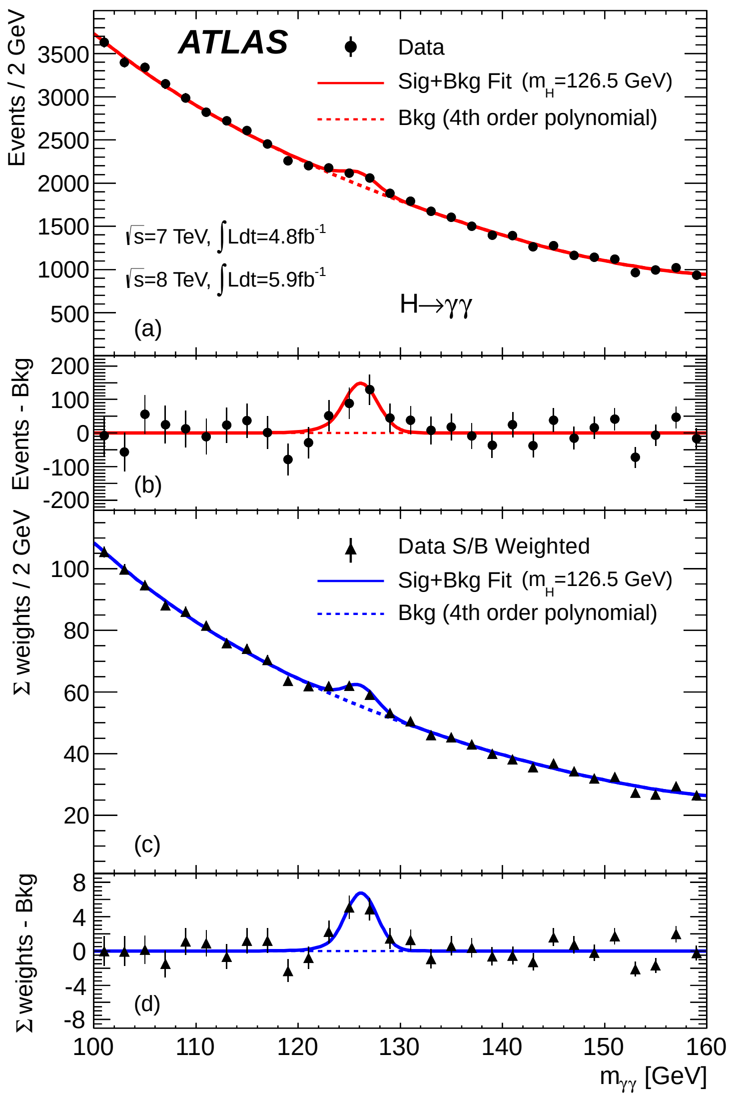
Higgs boson mass and the scale of new physics



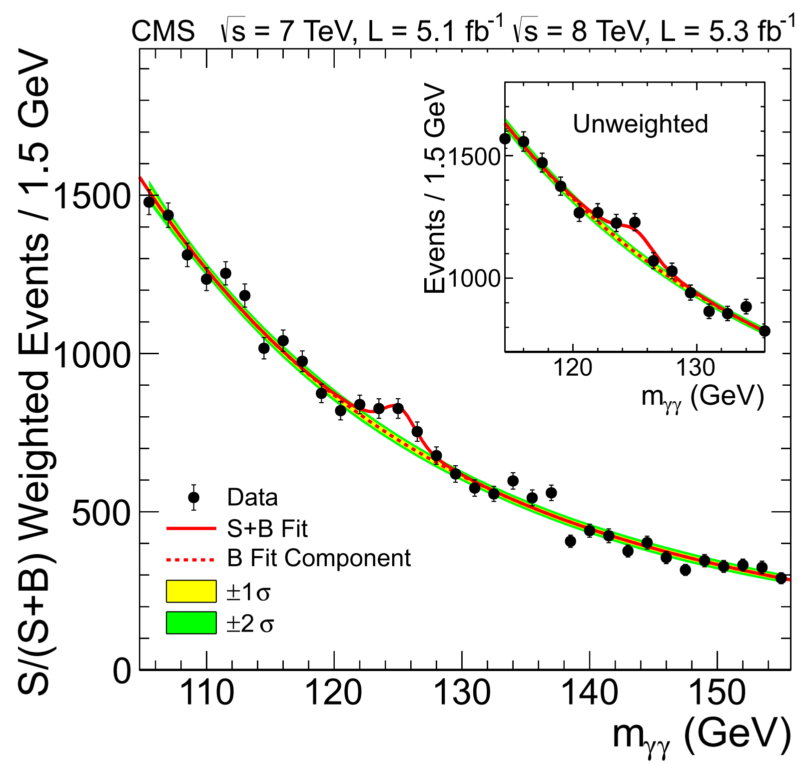
Mikhail Shaposhnikov

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

July 4, 2012, Higgs at ATLAS and CMS



CMS



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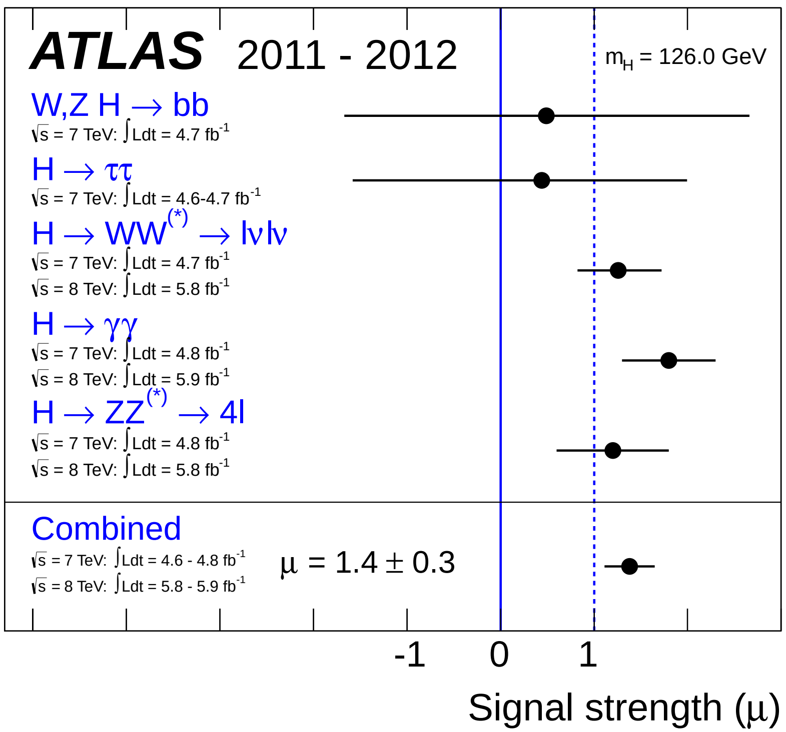

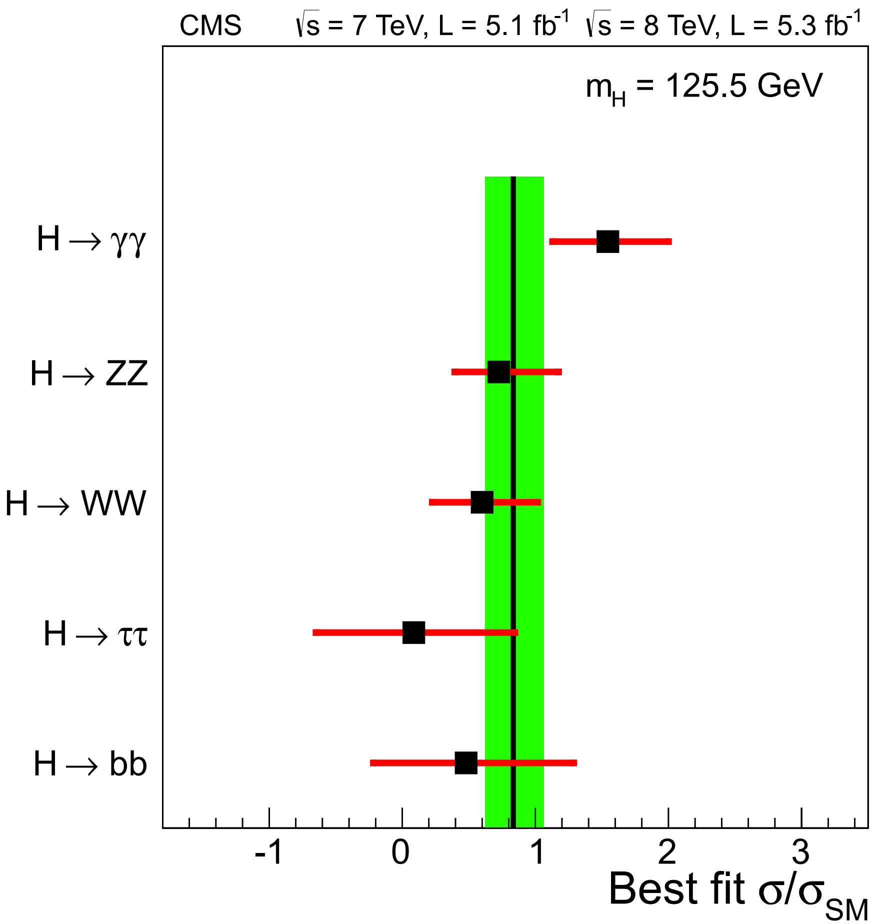

Kyoto, November 2012

According to CMS,

$$M_H = \mathbf{125.8 \pm 0.4}(\text{stat}) \pm \mathbf{0.5}(\text{syst})\,\mathbf{GeV},$$

According to ATLAS,

$$M_H = \mathbf{126.0 \pm 0.4}(\text{stat}) \pm \mathbf{0.4}(\text{syst})\,\mathbf{GeV}.$$

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Suppose that this is indeed the Higgs boson of the SM. What does it mean for high energy physics?

Possible answer

- There is no new energy scale between the Fermi and Planck scales
- Electroweak scale is determined by Planck physics
- New physics responsible for dark matter, baryon asymmetry of the universe and neutrino masses is hidden below the Fermi scale

Outline

- What did we know about the Higgs boson mass before its discovery?
- Higgs mass from asymptotically safe SM+gravity
- New physics between the Fermi and Planck scales?
- Higgs mass from inflation
- New physics below the Fermi scale
- Conclusions

Self-consistency of the SM

Within the SM the mass of the Higgs boson is an arbitrary parameter which can have any value (if all other parameters are fixed) from

$$m_{\mathrm{meta}} \simeq 111 \text{ GeV (metastability bound)}$$

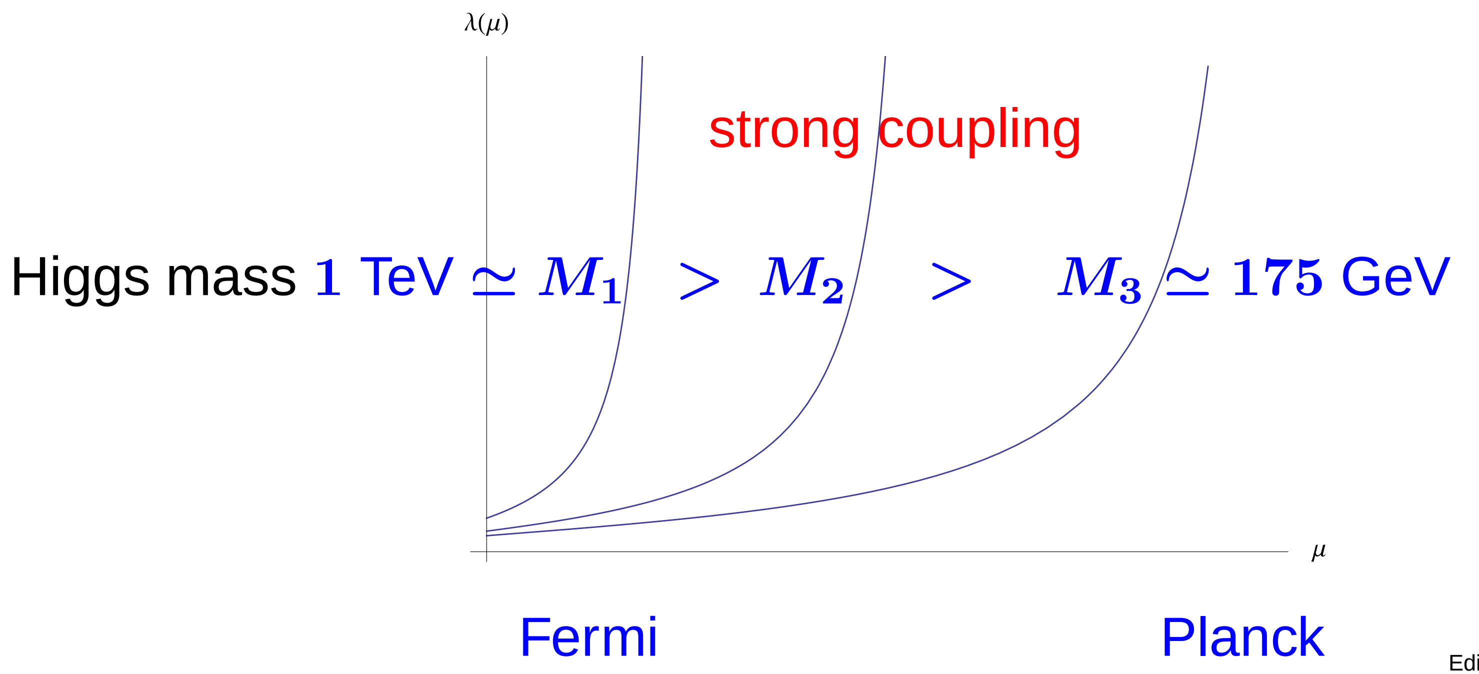
to

$$m_{\mathrm{Landau}} \simeq 1 \text{ TeV (triviality bound)}$$

Triviality bound

L. Maiani, G. Parisi and R. Petronzio ’77; Lindner ’85; T. Hambye and K. Riesselmann ’96;...

The Higgs boson self-coupling has a Landau pole at some energy determined by the Higgs mass. For $M_H \simeq m_{\mathbf{Landau}} \simeq 1$ TeV the position of this pole is close to the electroweak scale.



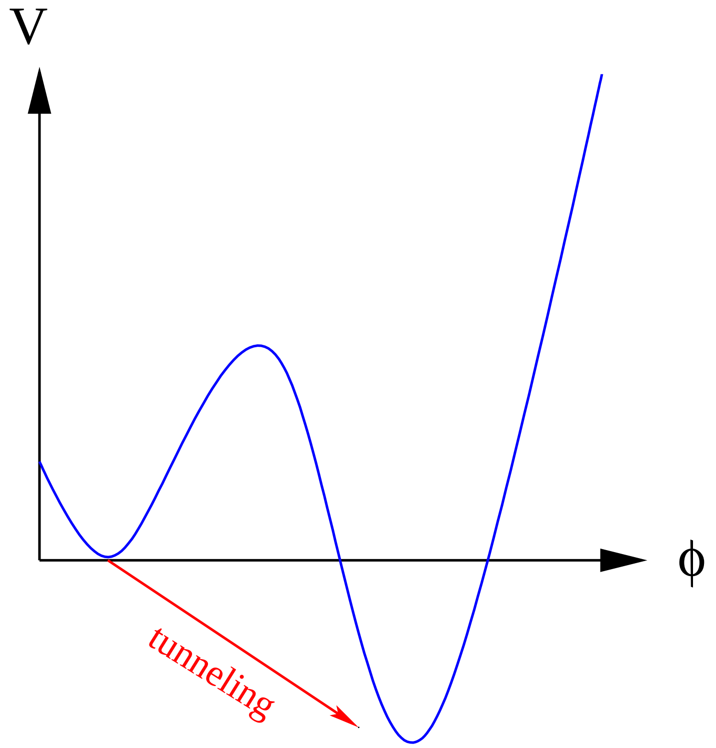
Triviality bound

If $m_H < m_{\mathbf{max}} \simeq \mathbf{175}$ GeV the Landau pole appears at energies higher than the Planck scale $E > M_P$.

LHC: The Standard Model is weakly coupled all the way up to the Planck scale

Metastability bound

Krasnikov '78, Hung '79; Politzer and Wolfram '79; Altarelli and Isidori '94; Casas, Espinosa and Quiros '94,'96;...; Ellis, Espinosa, Giudice, Hoecker, Riotto '09;...



The life-time of our vacuum is smaller than the age of the Universe if $m_H < m_{\mathbf{meta}}$, with $m_{\mathbf{meta}} \simeq 111$ GeV Espinosa, Giudice, Riotto '07

Metastability bound

If the Higgs mass happened to be smaller than $m_{\mathrm{meta}} \simeq 111$ GeV, we would be forced to conclude that there must be some new physics beyond the SM, which stabilizes the SM vacuum.

However, already since LEP we know that $m_H > m_{\mathrm{meta}}$ so that new physics is not needed from this point of view.

LHC: SM is a consistent effective theory all the way up to the Planck scale!

Higgs boson mass predictions

Though the Higgs mass cannot be predicted within the Standard Model, embedding it into larger context may fix M_H.

Compilation of 81 predictions, Thomas Schücker (as of November 2, 2010)

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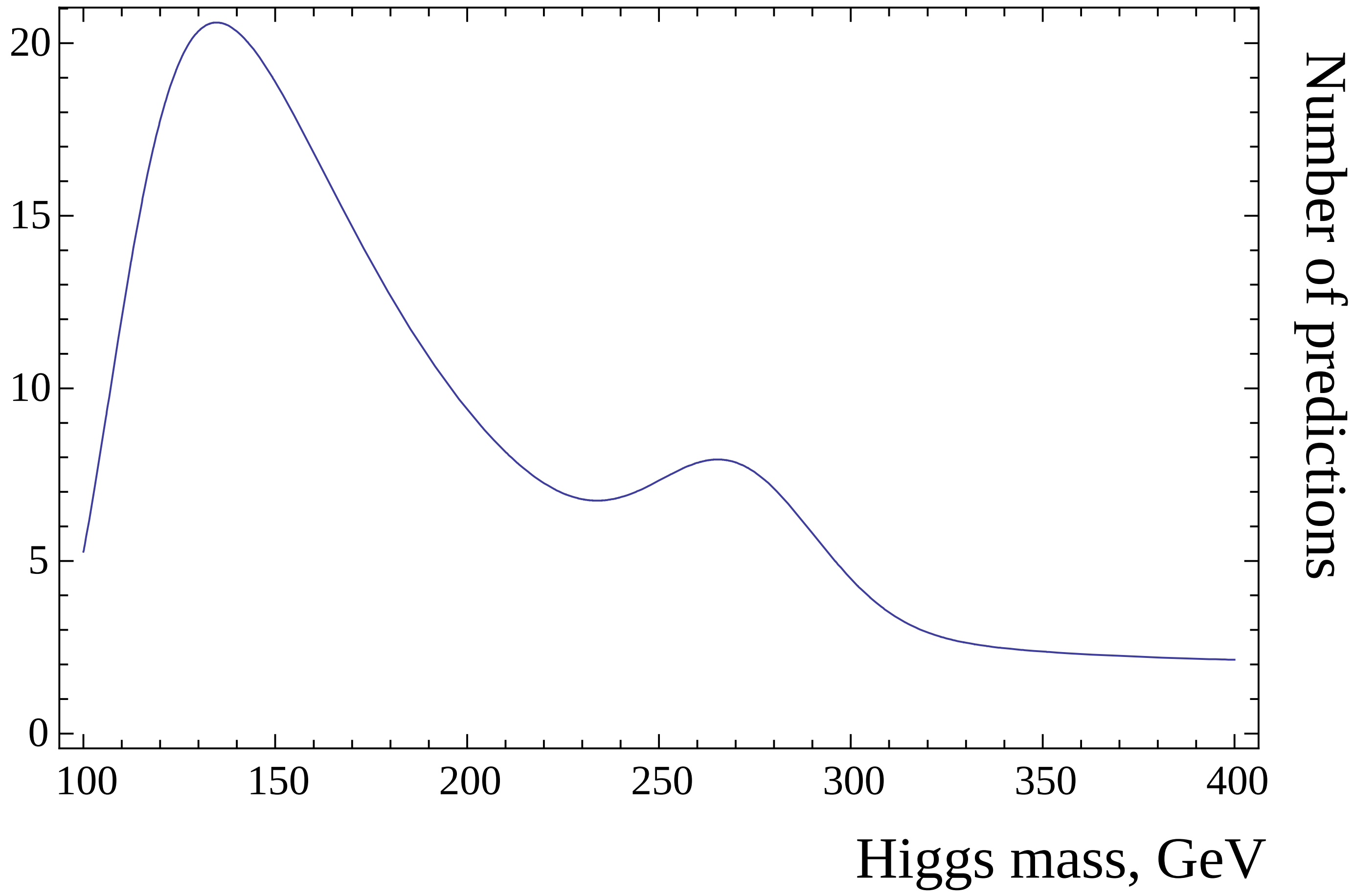
- The most precise prediction: $m_H = 161.8033989$ by El Naschie
- The highest number of predictions by one person (Gogoladze): 12
- No predictions in intervals:

  $600 - 739,\ 781 - 1800,\ 2000 - 10^{18}$ GeV

Bayesian approach

(as of November 2, 2010)



Bayesian “prediction” : $m_H \simeq 140$ GeV

Extract from M.S., Wetterich '09:

"Asymptotic safety of gravity and the Higgs boson mass"

"... This results in $\boldsymbol{M_H = m_{crit} = 126}$ GeV, with only a few GeV uncertainty..."

Also, the same value is a critical point for Higgs inflation

Bezrukov, M.S., '09

Higgs mass from asymptotically safe gravity

What if gravity is asymptotically safe?

Asymptotic safety = existence of non-Gaussian UV fixed point for gravity Weinberg '79. Though the theory is non-renormalizable, it is predictive and self-consistent.

Possible consequence: SM + Gravity is a final theory

To be true: all the couplings of the SM must be asymptotically safe or asymptotically free

Problem for:

- U(1) gauge coupling g_1, $\mu\frac{dg_1}{d\mu} = \beta_1^{\rm SM} = \frac{41}{96\pi^2} g_1^3$
- Scalar self-coupling λ, $\mu\frac{d\lambda}{d\mu} = \beta_\lambda^{\rm SM} =$

$$= \frac{1}{16\pi^2}\left[(24\lambda + 12h^2 - 9(g_2^2 + \frac{1}{3}g_1^2))\lambda - 6h^4 + \frac{9}{8}g_2^4 + \frac{3}{8}g_1^4 + \frac{3}{4}g_2^2 g_1^2\right]$$

- Fermion Yukawa couplings, t-quark in particular h, $\mu\frac{dh}{d\mu} = \beta_h^{\rm SM} =$

$$= \frac{h}{16\pi^2}\left[\frac{9}{2}h^2 - 8g_3^2 - \frac{9}{4}g_2^2 - \frac{17}{12}g_1^2\right]$$

Landau pole behaviour

Gravity contribution to RG running

Let x_j is a SM coupling. Gravity contribution to RG:

$$\mu \frac{dx_j}{d\mu} = \beta_j^{\mathrm{SM}} + \beta_j^{grav} \ .$$

On dimensional grounds

$$\beta_j^{grav} = \frac{a_j}{8\pi} \frac{\mu^2}{M_P^2(\mu)} x_j \ .$$

where

$$M_P^2(\mu) = M_P^2 + 2\xi_0 \mu^2 \ ,$$

with $M_P = (8\pi G_N)^{-1/2} = 2.4 \times 10^{18}$ GeV, $\xi_0 \approx 0.024$

from a numerical solution of FRGE

Computations of a_j are ambiguous and controversial

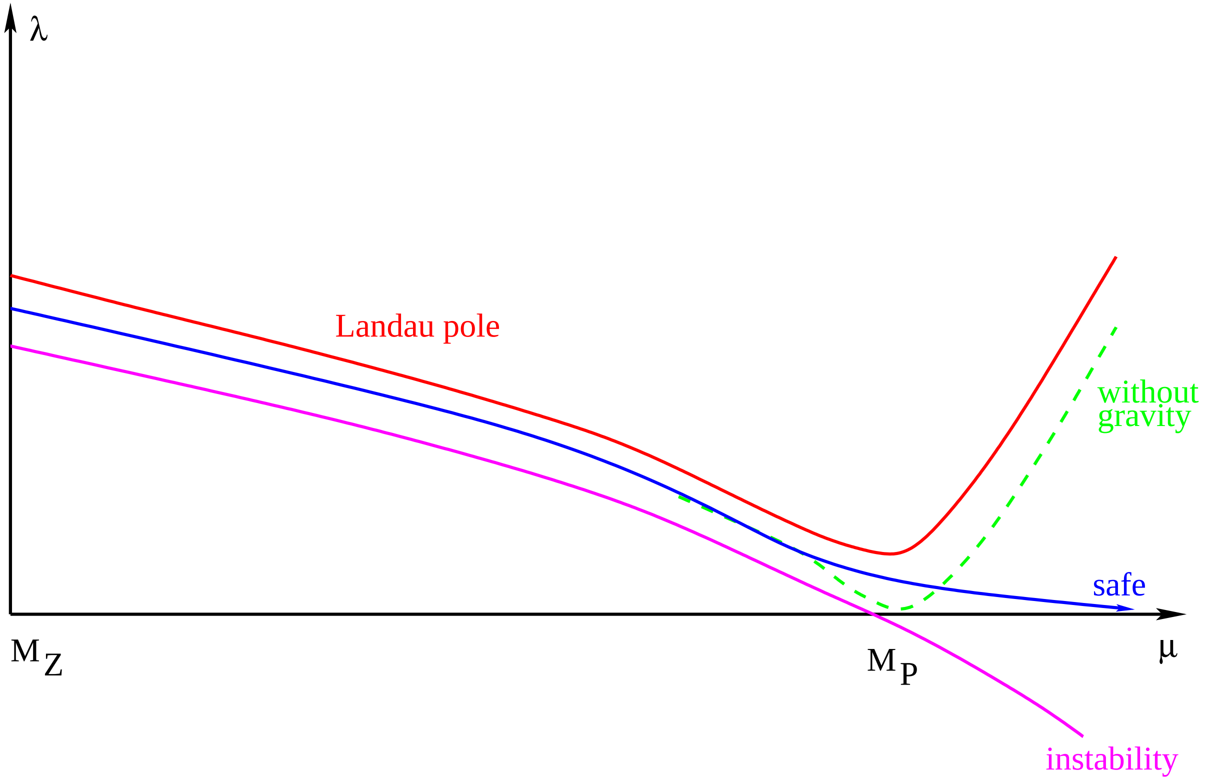
Robinson and Wilczek '05, Pietrykowski '06, Toms '07&'08, Ebert, Plefka and Rodigast '07, Narain and Percacci '09, Daum, Harst and Reuter '09, Zanusso et al '09, Folkerts, Litim and Pawlowski '11, Ellis, Mavromatos '12 ...

- Many works get for gauge couplings a universal value $a_1 = a_2 = a_3 < 0$: U(1) gauge coupling get asymptotically free in asymptotically safe gravity
- $a_\lambda \simeq 2.6 > 0$ according to Percacci and Narain '03 for scalar theory coupled to gravity
- $a_h >< 0$?? The case $a_h > 0$ is not phenomenologically acceptable - only massless fermions are admitted

Suppose that indeed $a_1 < 0,\ a_h < 0,\ a_\lambda > 0$, what is found in a number of computations. Then the Higgs mass is predicted to be coming from solution of equation

$$\lambda(M_P) = 0$$

with uncertainty of few hundreds of MeV. Simultaneously, it is required that $\beta_\lambda(M_P) \ll 1$.



Computation of M_H

Definition: "$\overline{MS}$ benchmark Higgs mass M_{crit}" is defined from equations

$$\lambda(\mu_0) = 0, \quad \beta_\lambda^{\mathrm{SM}}(\mu_0) = 0$$

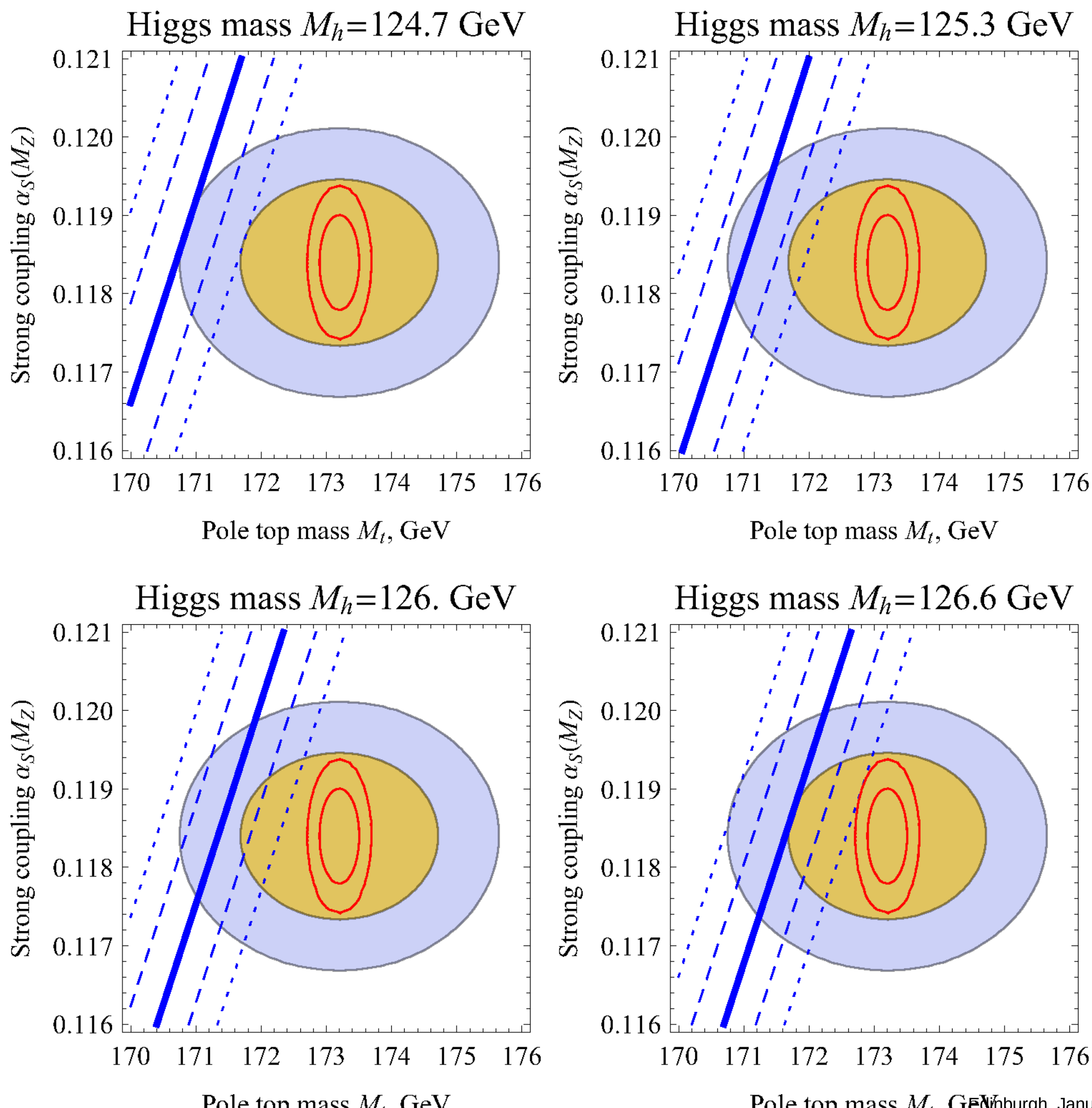
together with parameter μ_0, assuming that all parameters of the SM, except the Higgs mass, are fixed.

Most recent computation of M_{crit} (Bezrukov et al, May 13, 2012), incorporating $\mathcal{O}(\alpha\alpha_s)$ two-loop matching and 3-loop running of coupling constants (Chetyrkin, Zoller, May 13, 2012)

$$m_{crit} = [129.0 + \frac{m_t - 172.9}{1.1} \times 2.2 - \frac{\alpha_s - 0.1184}{0.0007} \times 0.56] \text{ GeV },$$

Theoretical uncertainties: ± 1.2 GeV (different sources are summed quadratically) or ± 2.3 GeV (different sources are summed linearly).

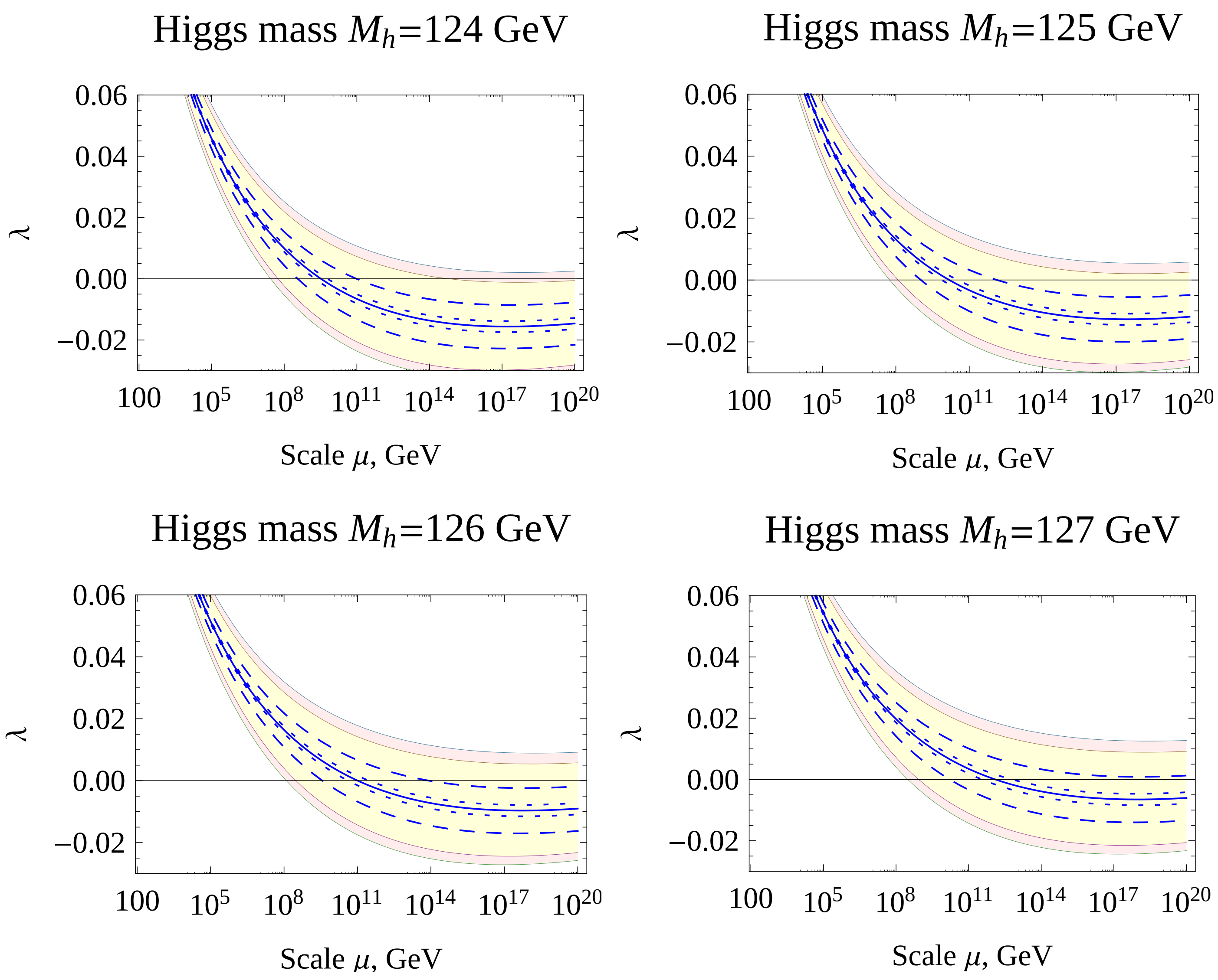
Effect of contributions $\propto y_t^4, y_t^2\lambda^2, \lambda^4$ (Degrassi et al., May 29, 2012): shift of the Higgs mass by $100 - 200$ MeV. Quadratic theoretical uncertainty is reduced to ~ 0.8 GeV.


Higgs mass M_h=124.7 GeV
Higgs mass M_h=125.3 GeV
Higgs mass M_h=126. GeV
Higgs mass M_h=126.6 GeV
Strong coupling $\alpha_S(M_Z)$
Pole top mass M_t, GeV
0.116
0.117
0.118
0.119
0.120
0.121
170
171
172
173
174
175
176

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

- Compute remaining two-loop $\mathcal{O}(\alpha^2)$ corrections to pole - $\overline{\mathrm{M}S}$ matching for the Higgs mass and top masses. Theoretical uncertainty can reduced to $\sim \mathbf{0.5}$ 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. The same conclusion - Alekhin et al, '12
- 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

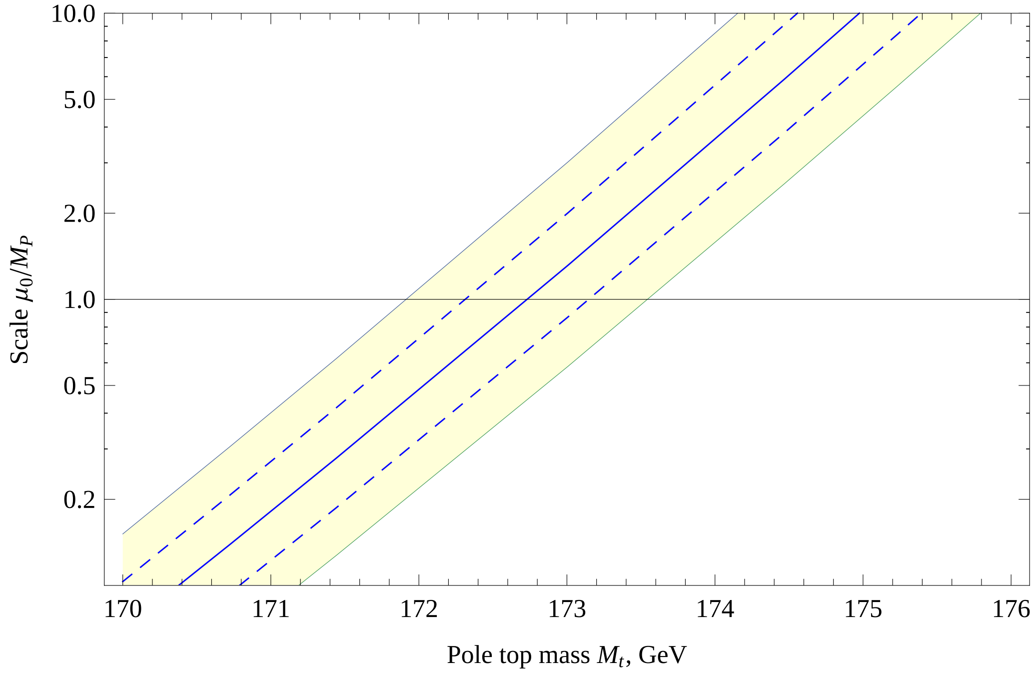


New Physics between the Fermi and Planck scales?

From two equations

$$\lambda(\mu_0) = 0, \quad \beta_\lambda^{\mathrm{SM}}(\mu_0) = 0$$

one can determine not only the Higgs mass, but also the scale μ_0.



μ_0 determined by the EW physics gives the Planck scale, $\mu_0 \simeq M_P$!

Numerical coincidence?

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

This relation is generically spoiled if new physics exists between the Fermi and Planck scales.

$$\Downarrow$$

Argument in favour of absence of new physics scales between Fermi and Planck.

Higgs mass and inflation

non-minimal coupling of Higgs field to gravity

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

Feynman, Brans, Dicke,...

Consider large Higgs fields h.

- Gravity strength: $M_P^{\text{eff}} = \sqrt{M_P^2 + \xi h^2} \propto h$
- All particle masses are $\propto h$

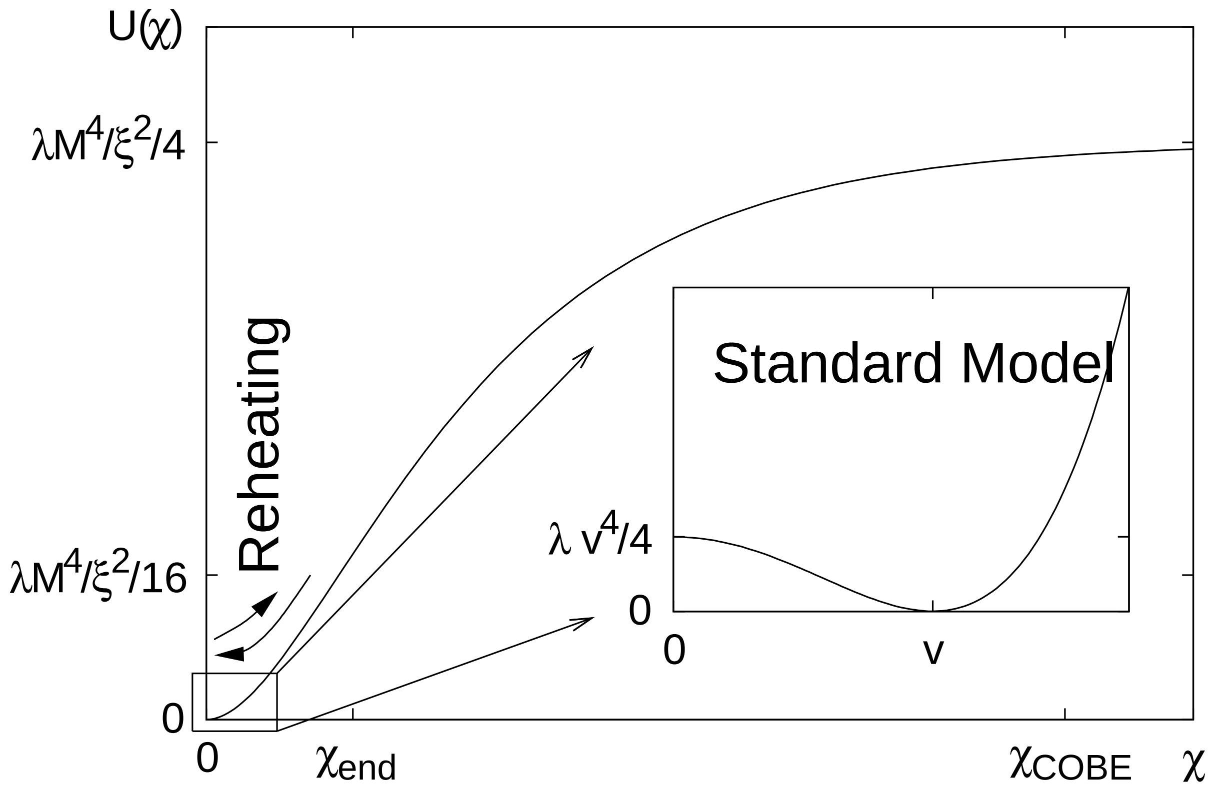
For $h > \frac{M_P}{\xi}$ (classical) physics is the same (M_W / M_P^{eff} does not depend on h)!

Existence of effective flat direction, necessary for successful inflation.

Formalism: go from Jordan frame to Einstein frame with the use of conformal transformation:

$$\hat{g}_{\mu\nu} = \Omega^2 g_{\mu\nu} \ , \quad \Omega^2 = 1 + \frac{\xi h^2}{M_P^2}$$

Potential in Einstein frame



Inflaton potential and observations

If inflaton potential is known one can make predictions and compare them with observations.

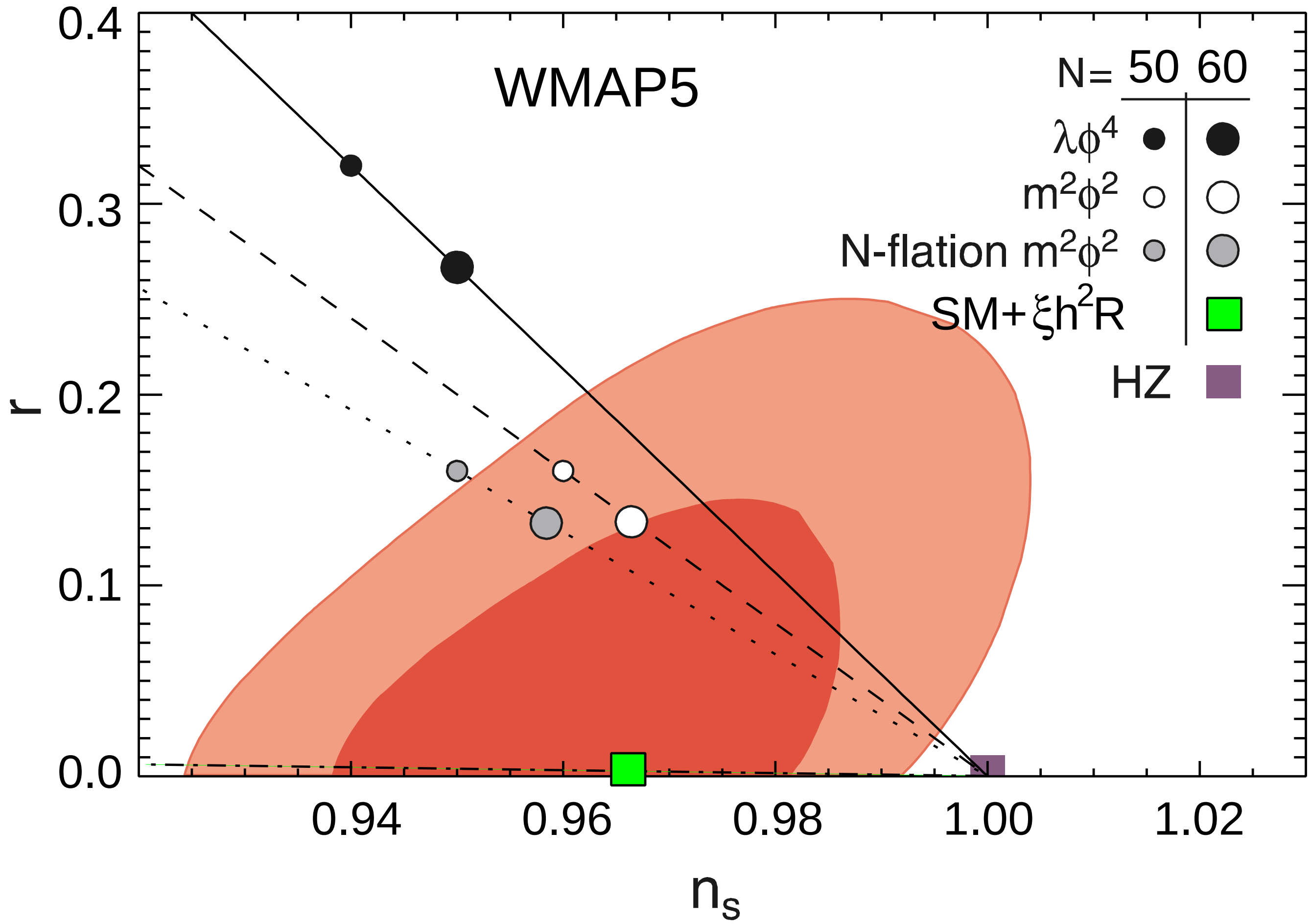
- $\delta T/T$ at the WMAP normalization scale ~ 500 Mpc
- The value of spectral index n_s of scalar density perturbations

$$\left\langle \frac{\delta T(x)}{T}\frac{\delta T(y)}{T}\right\rangle \propto \int \frac{d^3k}{k^3} e^{ik(x-y)} k^{n_s-1}$$

- The amplitude of tensor perturbations $r = \frac{\delta\rho_s}{\delta\rho_t}$

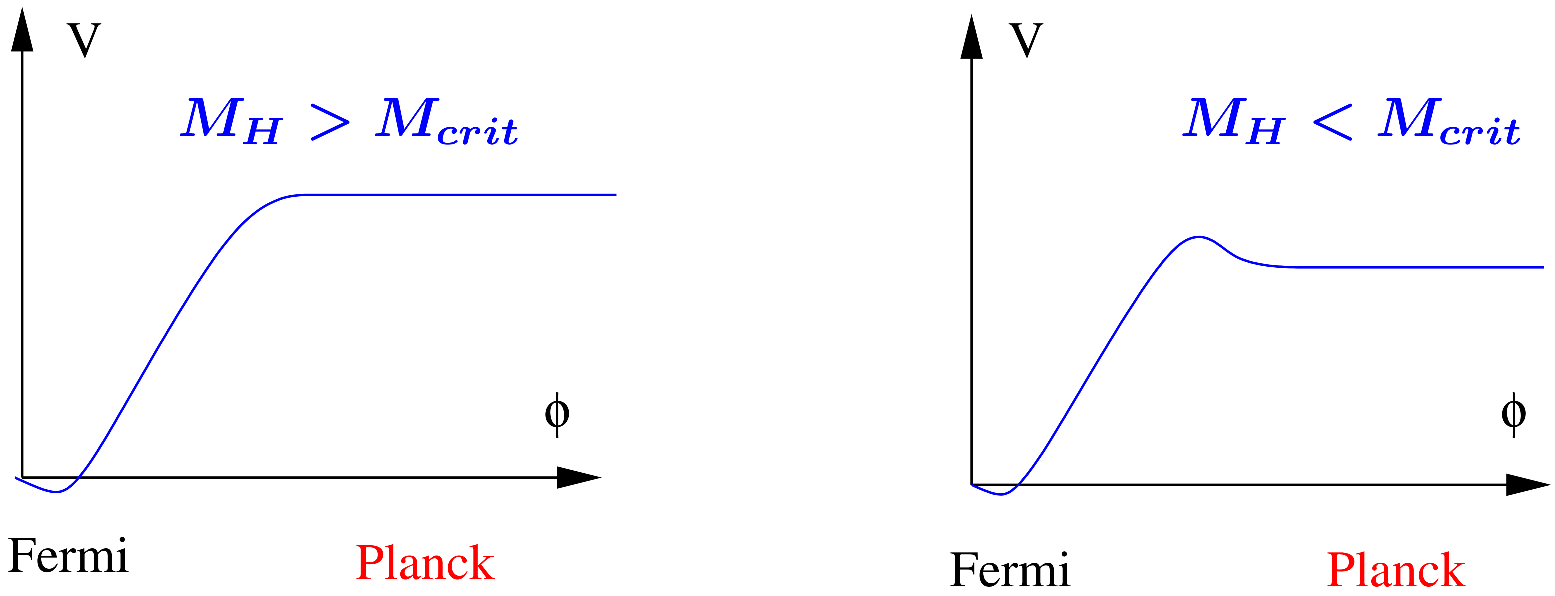
These numbers can be extracted from WMAP observations of cosmic microwave background. Higgs inflation: one new parameter, $\xi \Longrightarrow$ two predictions.

CMB parameters—spectrum and tensor modes



Inflation and the Higgs mass

Radiative corrections to inflationary potential: Higgs inflation works only for $\lambda(M_P/\sqrt{(}\xi)) > 0$ (Bezrukov, MS). Numerically, $M_H > M_{crit} - 200$ MeV. The equality leads to the minimal value of non-minimal coupling, $\xi \simeq 700$, what extends the region of weak coupling of the theory.



New Physics below the Fermi scale

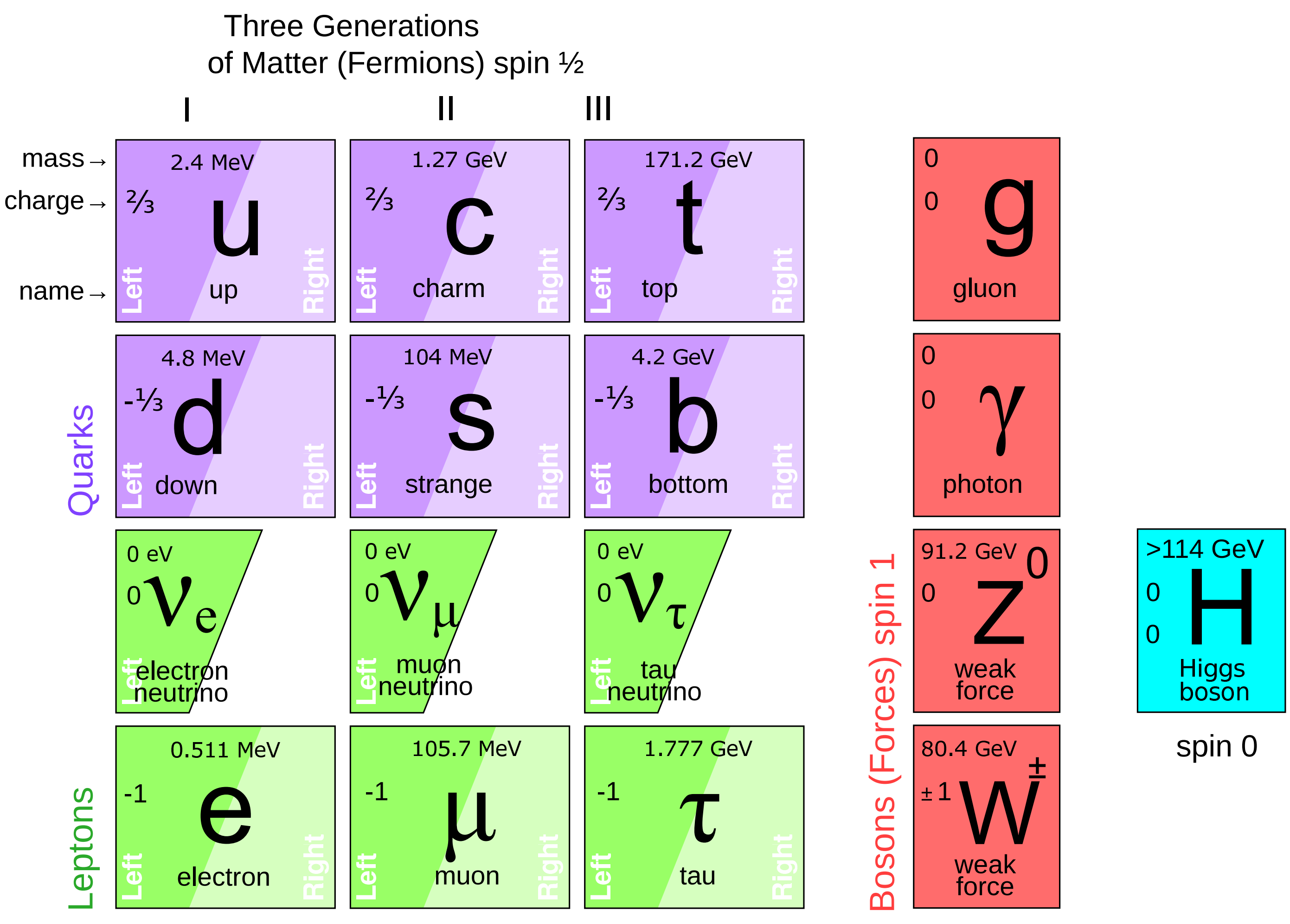
SM + Gravity and no new physics?

The most conservative hypothesis: we have Standard Model + Gravity and nothing else.

Ruled out by:

- Observations of neutrino oscillations (in the SM neutrinos are massless and do not oscillate)
- Evidence for Dark Matter (SM does not have particle physics candidate for DM)
- No antimatter in the Universe in amounts comparable with matter (baryon asymmetry of the Universe is too small in the SM)

the SM


Three Generations
of Matter (Fermions) spin ½
I
II
III
mass →
charge →
name →
2.4 MeV
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up
1.27 GeV
⅔
c
charm
171.2 GeV
⅔
t
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4.8 MeV
-⅓
d
down
104 MeV
-⅓
s
strange
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b
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tau
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Right
Quarks
Leptons
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photon
91.2 GeV
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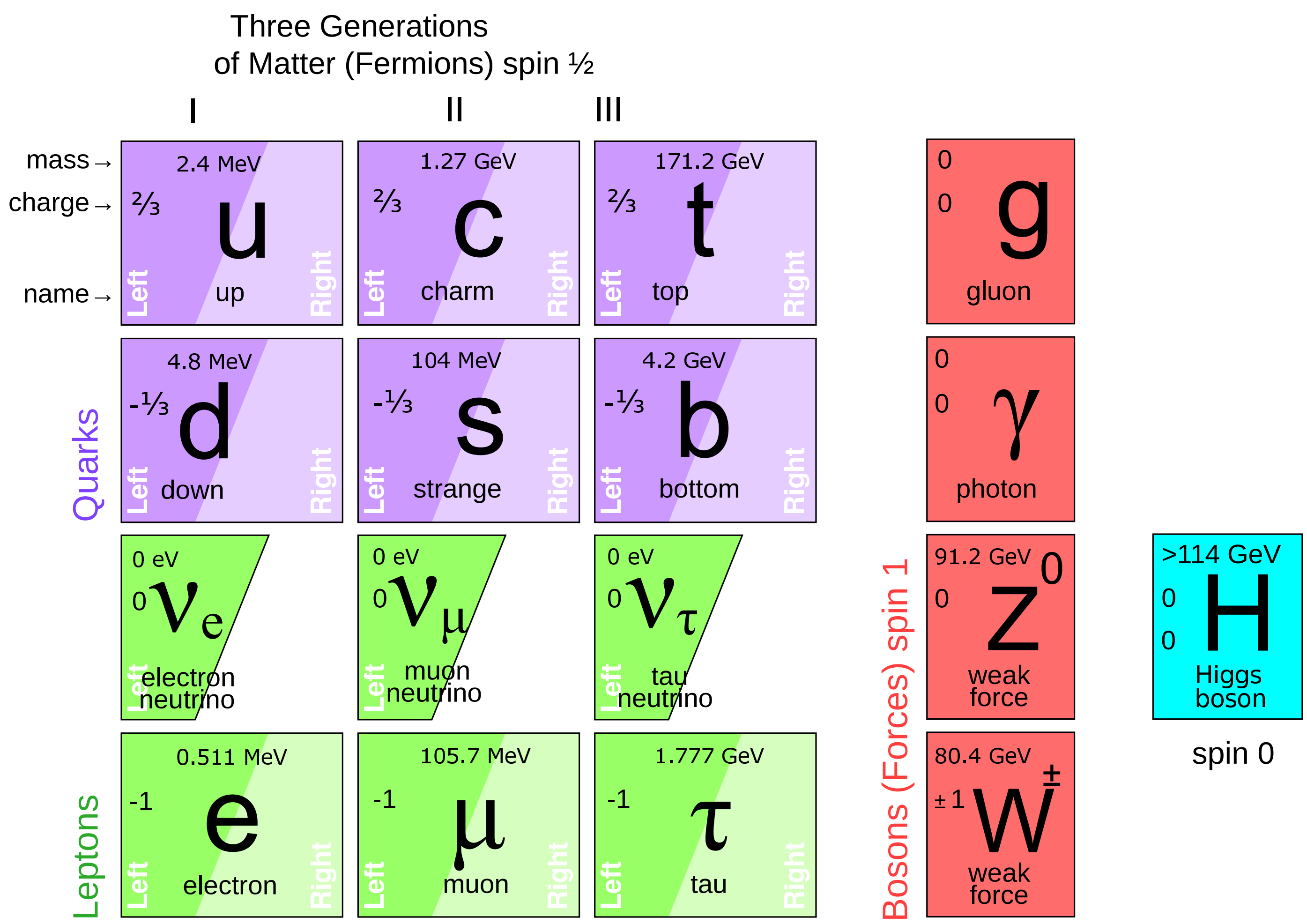
Z0
weak force
80.4 GeV
±1
W±
weak force
Bosons (Forces) spin 1
>114 GeV
0
0
H
Higgs boson
spin 0


Right-handed neutrinos.
What else?

the SM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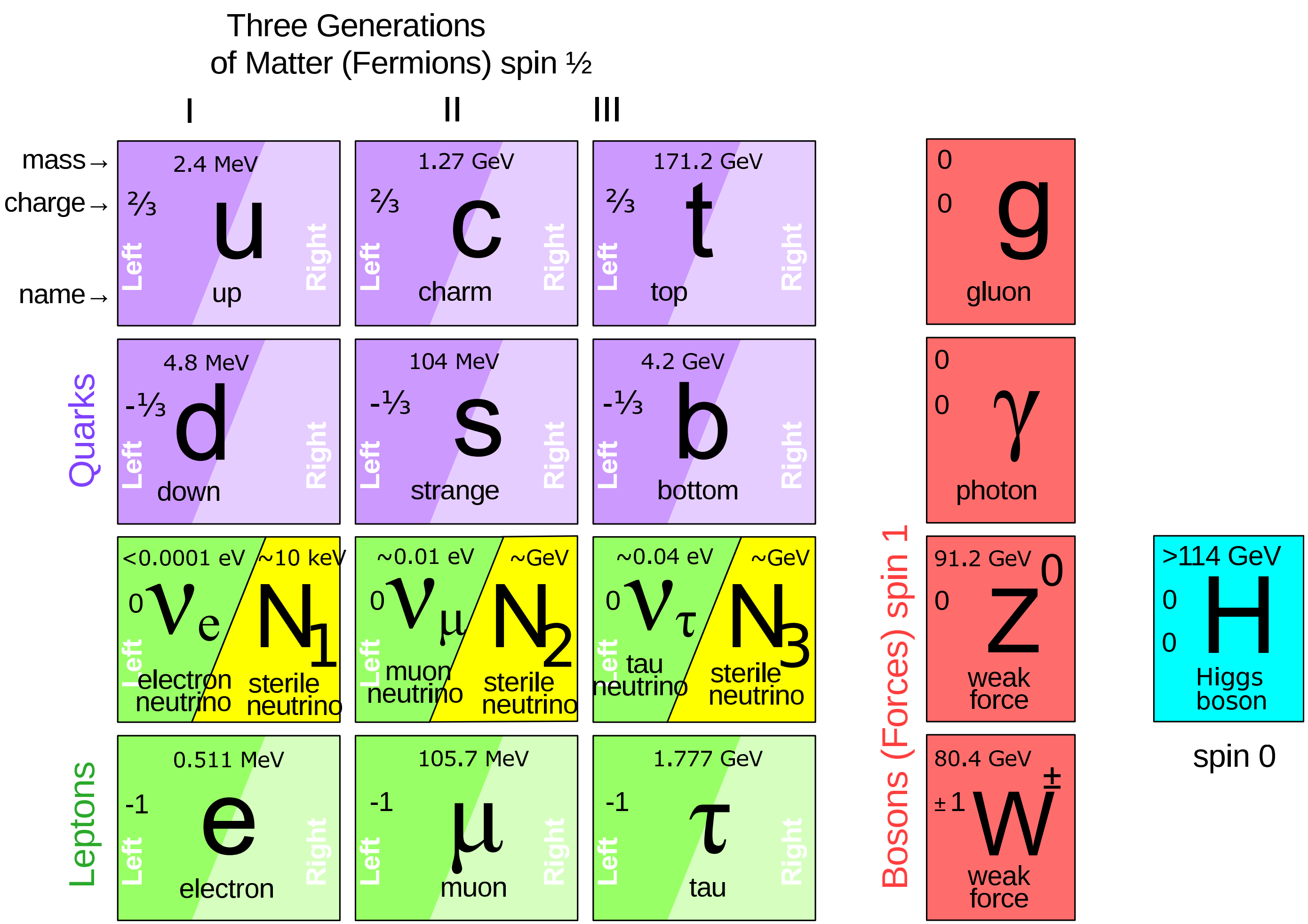
the νMSM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Quarks
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muon neutrino
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~GeV
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ντ
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80.4 GeV
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weak force
Bosons (Forces) spin 1
>114 GeV
0
0
H
Higgs boson
spin 0

SM + Gravity + new physics below the EW scale

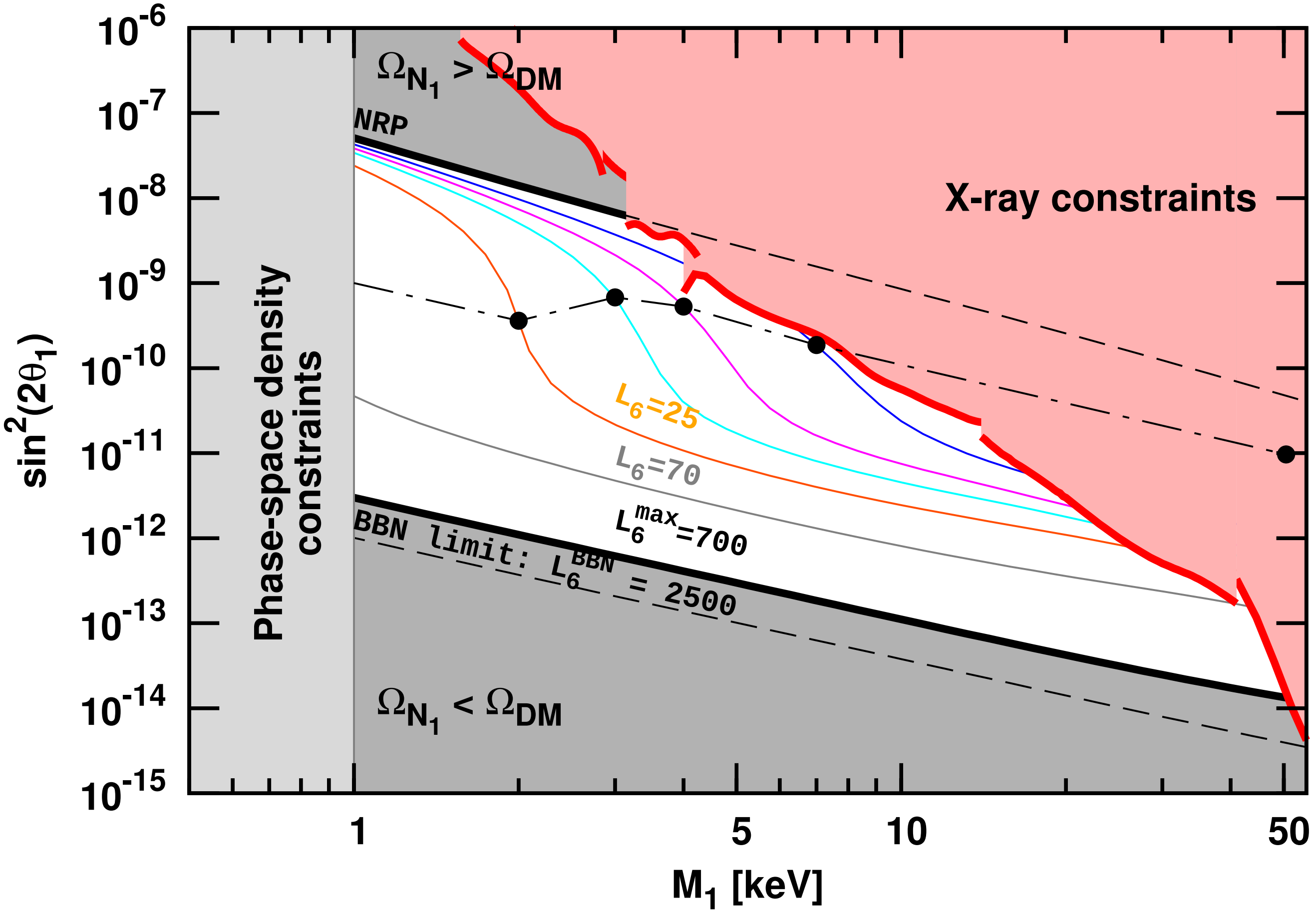
The less conservative hypothesis: there are no intermediate energy scales between the Fermi scale 100 GeV and the Planck scale 10^{18} GeV.

Role of N_1 with mass in keV region: dark matter

Role of $N_2, \ N_3$ with mass in 100 MeV – GeV region: “give” masses to neutrinos and produce baryon asymmetry of the Universe, all due to the Higgs boson

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

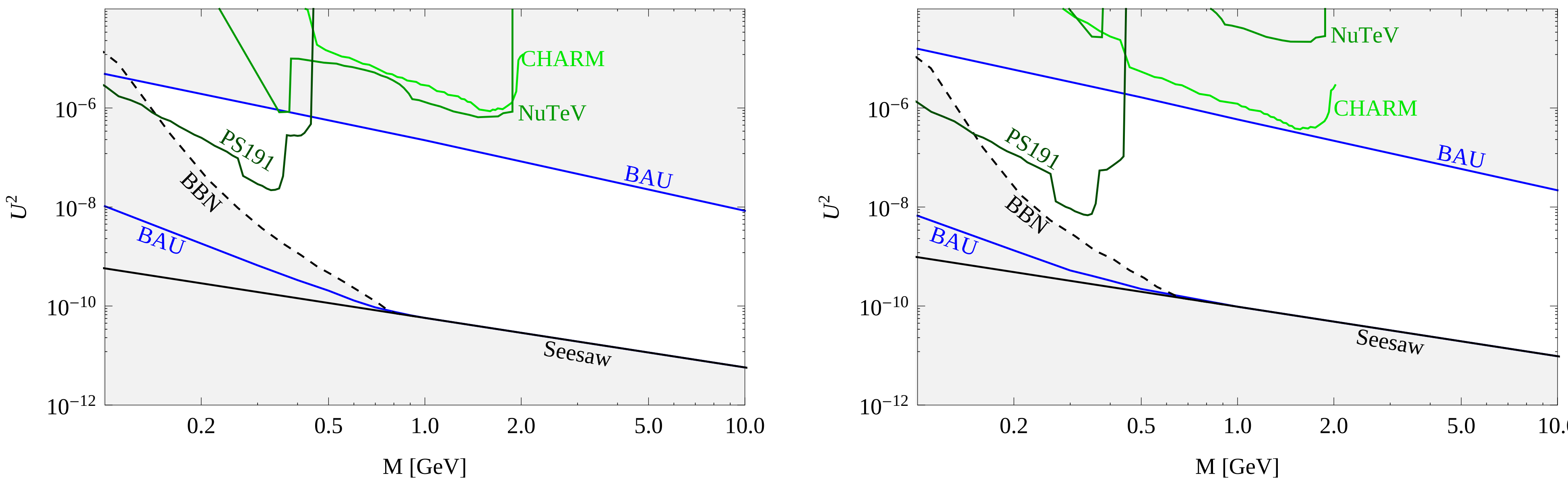


Important: DM sterile neutrino production requires the presence of large, $\Delta L/L > 2 \times 10^{-3}$ lepton asymmetry at temperature $T \sim 100$ MeV. It can only be produced in the νMSM.

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 $N_{2,3}$ to active neutrinos cannot be too large
- Neutrino masses. Mixing angle of $N_{2,3}$ to active neutrinos cannot be too small
- BBN. Decays of $N_{2,3}$ must not spoil Big Bang Nucleosynthesis
- Experiment. $N_{2,3}$ have not been seen yet



Constraints on U^2 coming from the baryon asymmetry of the Universe, from the see-saw formula, from the big bang nucleosynthesis and experimental searches. Left panel - normal hierarchy, right panel - inverted hierarchy. Canetti et al.

Crucial tests and experiments

Experiments, which will be done anyway

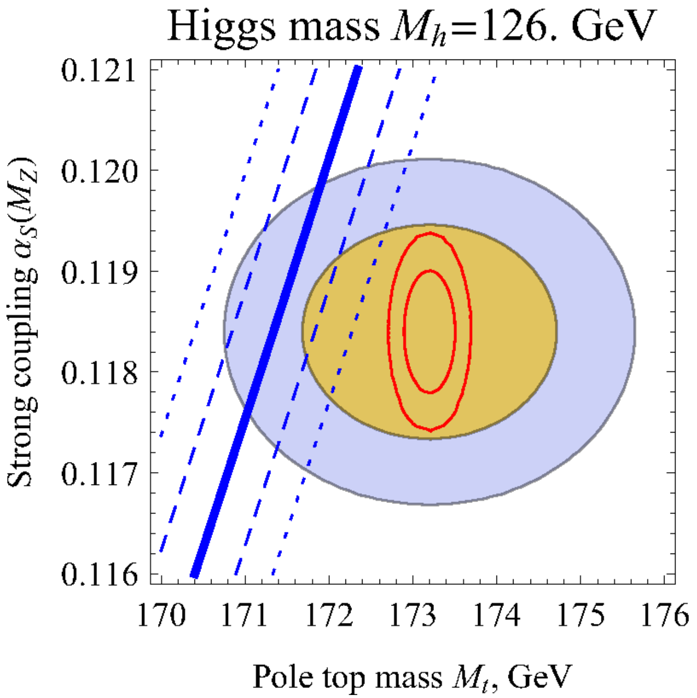
- Crucial experimental test - the LHC. The νMSM prediction - no deviations from the SM (Perhaps, LHCb upgrade to search for N?)
- WIMP searches: no WIMPS in the νMSM
- Unitarity of PMNS neutrino mixing matrix: θ_{13}, $\theta_{23} - \pi/4$, type of neutrino mass hierarchy, Dirac CP-violating phase
- Absolute neutrino mass. The νMSM prediction: $m_1 \lesssim 10^{-5}$ eV (from DM). Then $m_2 \simeq 5 \cdot 10^{-2}$eV, $m_3 \simeq 9 \cdot 10^{-3}$eV or $m_{2,3} \simeq 5 \cdot 10^{-2}$ eV.
  (Double β decay, Bezrukov)
  Normal hierarchy: $1.3 \text{ meV} < m_{\beta\beta} < 3.4 \text{ meV}$
  Inverted hierarchy: $13 \text{ meV} < m_{\beta\beta} < 50 \text{ meV}$
- Crucial cosmological test - precise measurements of cosmological parameters n_s, r, $\Delta n_s \simeq 0.004$

New dedicated experiments

High energy frontier

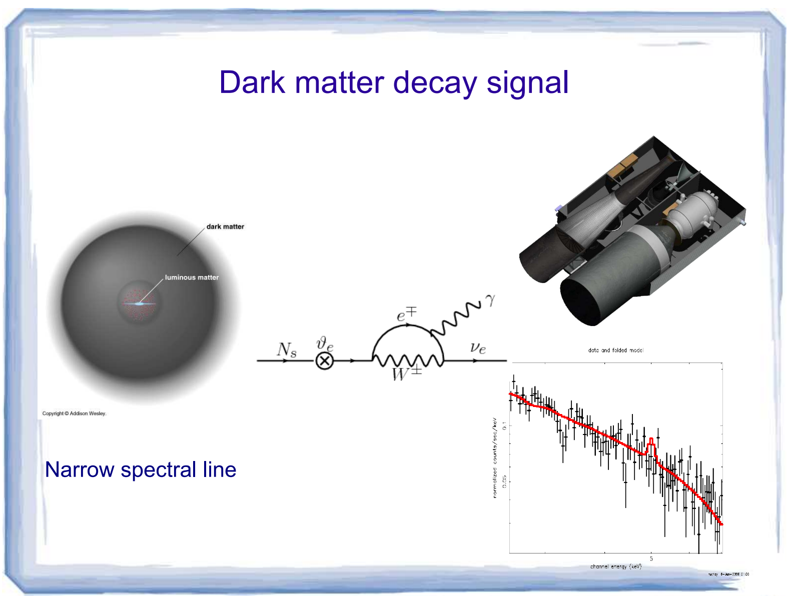
Construction of t-quark factory – e^+e^- or $\mu^+\mu^-$ linear collider with energy $\simeq 200 \times 200$ GeV.

Precise measurement of top and Higgs masses, to elucidate the relation between the electroweak and Planck scales.



Search for N_1

X-ray telescopes similar to *Chandra* or *XMM-Newton* but with better energy resolution: narrow X-ray line from decay $N_e \to \nu\gamma$

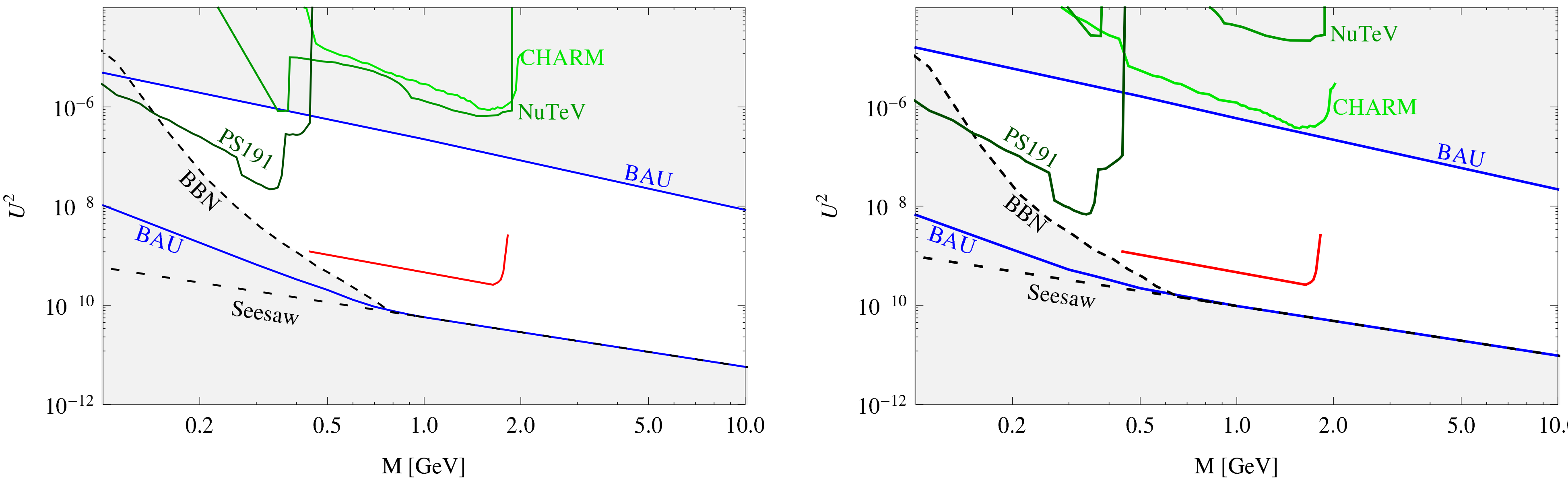


One needs:

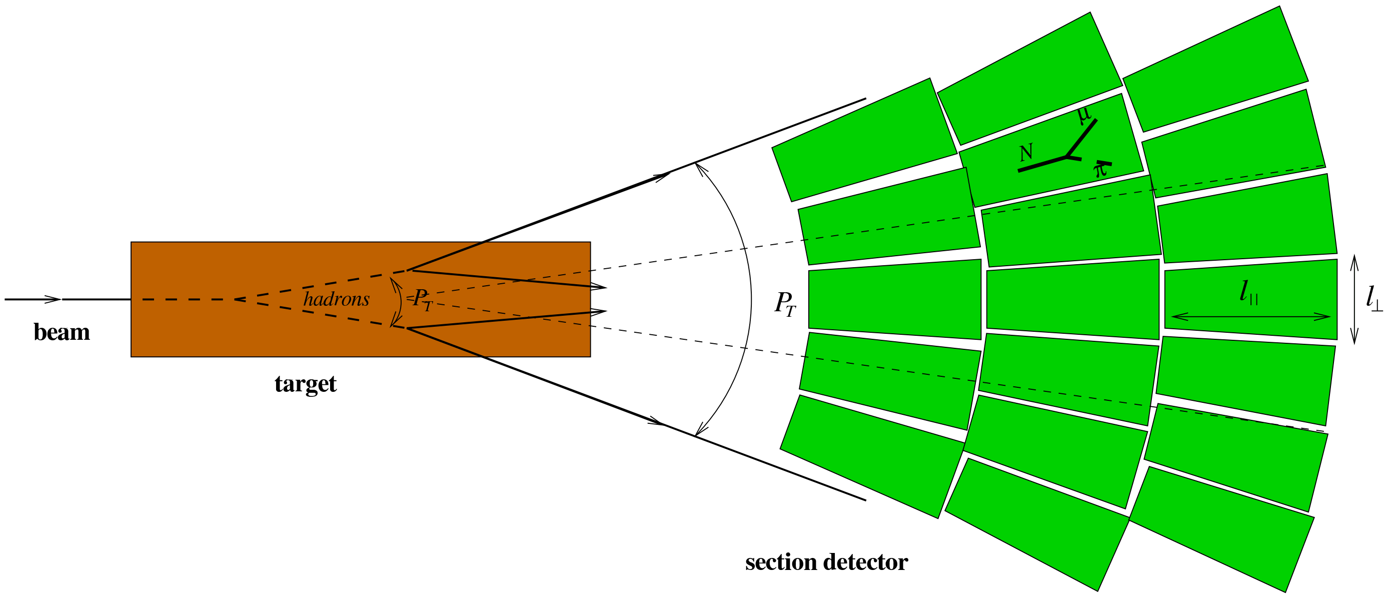
- Improvement of spectral resolution up to the natural line width ($\Delta E/E \sim 10^{-3}$).
- FoV $\sim 1^\circ$ (size of a dwarf galaxies).
- Wide energy scan, from $\mathcal{O}(100)$ eV to $\mathcal{O}(50)$ keV.

Search for N_2, N_3

Challenge - from baryon asymmetry: $\theta^2 \lesssim 5 \times 10^{-7} \left(\frac{\mathrm{GeV}}{M}\right)$ CERN SPS is the best existing machine to uncover new physics below the electroweak scale. For $l \sim 100$ m detector.



Gorbunov, MS



Sketch of the proposed section detector of several kilometer total length; each standard section of length $\boldsymbol{l_{||} \sim 100}$ m, height 5 m and width $\boldsymbol{l_\perp \sim 5}$ m may operate independently.

Conclusions

- LHC experiments provide a strong evidence that the SM is a self-consistent effective theory all the way up to the Planck scale.
- The case of $M_H = M_{crit}$ is very peculiar: if this is indeed the case, this is a strong indication for the absence of new energy scales between the Fermi and Planck scales
- The new physics responsible for neutrino masses, dark matter and baryon asymmetry of the Universe can be below the Fermi scale and associated with extension of the SM by 3 Majorana fermions with masses in keV - GeV region.
- There are plenty of experiments which can confirm or reject the minimal model