ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

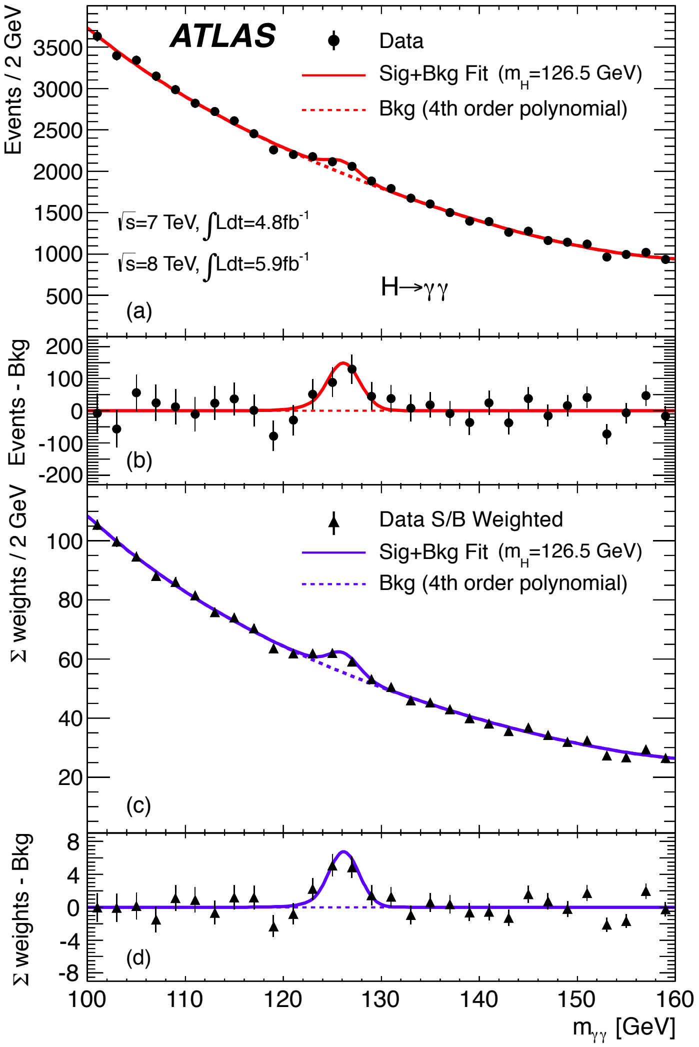
Inflation and LHC

Mikhail Shaposhnikov

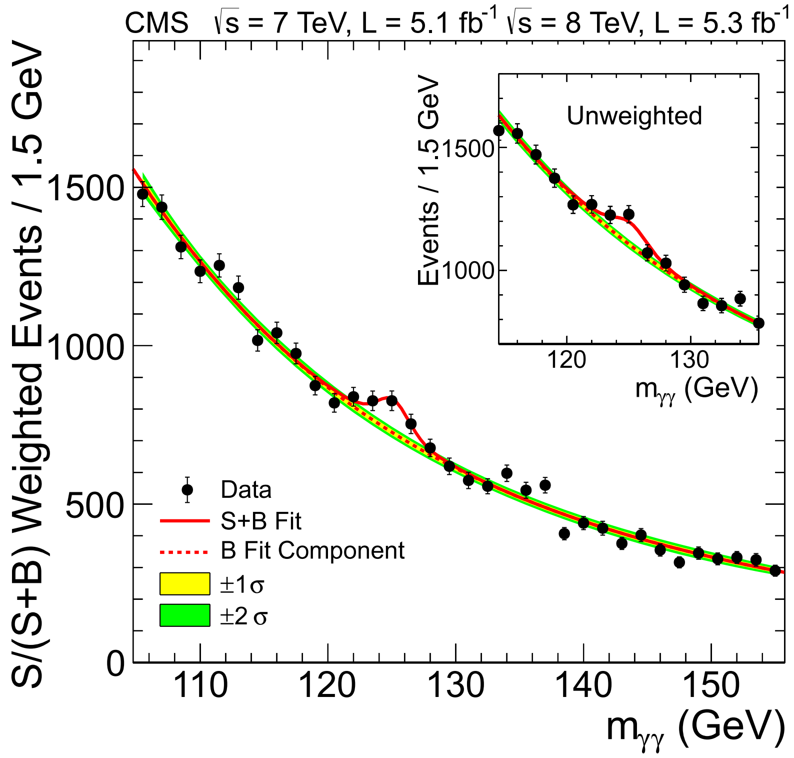
Seminar at LLR Ecole Polytechnique

LHC discoveries important for Cosmology

July 4, 2012, Higgs at ATLAS and CMS



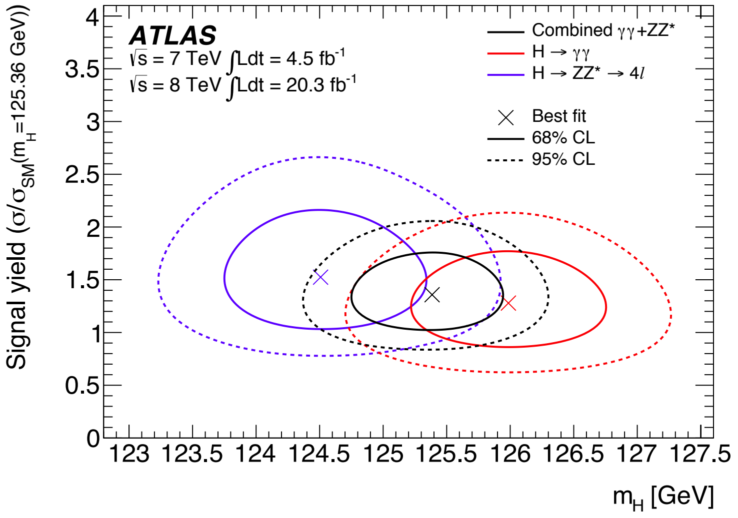
CMS

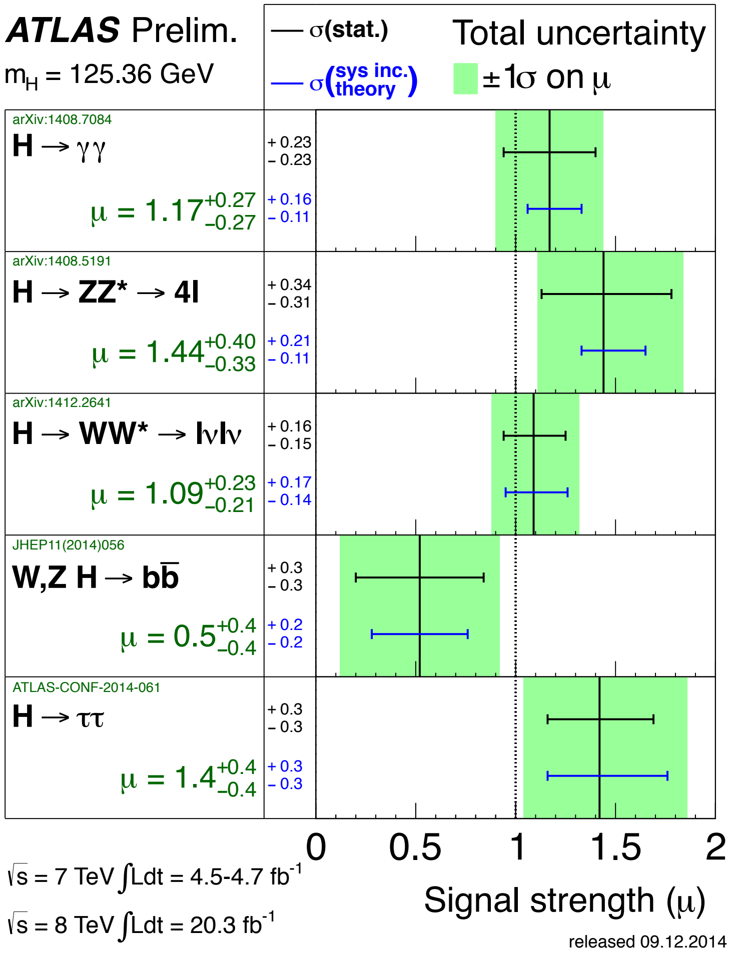


Higgs boson properties

Atlas - $M_H = \mathbf{125.36 \pm 0.41}$ GeV

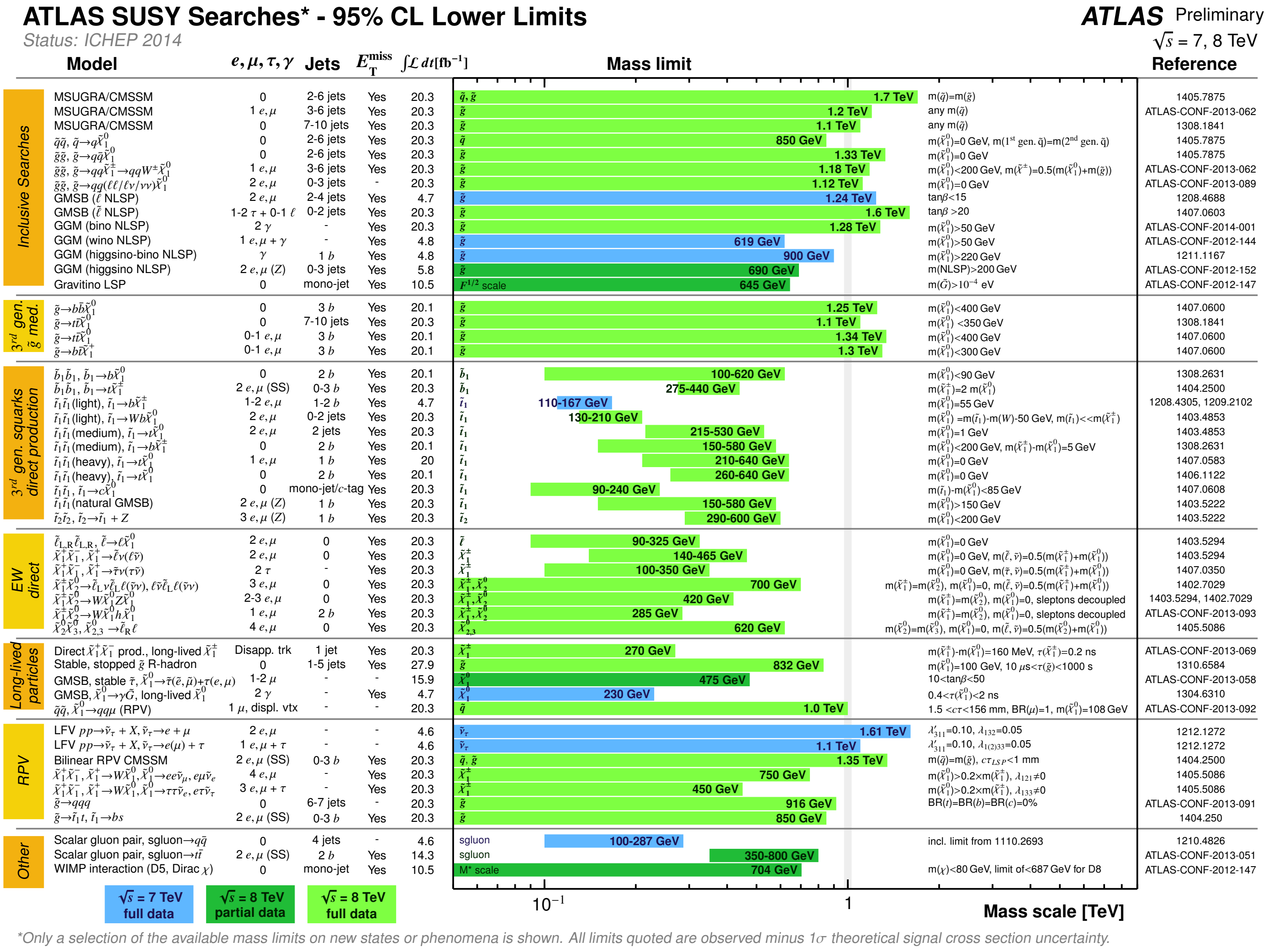
CMS - $M_H = \mathbf{125.03 \pm 0.29}$ GeV





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

Searches for new physics, SUSY



ATLAS SUSY Searches* - 95% CL Lower Limits

Status: ICHEP 2014

ATLAS Preliminary
$\sqrt{s}$ = 7, 8 TeV

	Model	e,μ,τ,γ	Jets	E_T^{miss}	$\int\mathcal{L}\,dt[\mathrm{fb}^{-1}]$	Mass limit			Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q},\tilde{g}$	1.7 TeV	$m(\tilde{q})=m(\tilde{g})$	1405.7875
	MSUGRA/CMSSM	1 e,μ	3-6 jets	Yes	20.3	$\tilde{g}$	1.2 TeV	any $m(\tilde{q})$	ATLAS-CONF-2013-062
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	$\tilde{g}$	1.1 TeV	any $m(\tilde{q})$	1308.1841
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$	850 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, m(1st gen. $\tilde{q}$)=m(2nd gen. $\tilde{q}$)	1405.7875
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$	1.33 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	1405.7875
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^{\pm}\to qqW^{\pm}\tilde{\chi}_1^0$	1 e,μ	3-6 jets	Yes	20.3	$\tilde{g}$	1.18 TeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}^{\pm})$=0.5($m(\tilde{\chi}_1^0)$+$m(\tilde{g})$)	ATLAS-CONF-2013-062
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e,μ	0-3 jets	-	20.3	$\tilde{g}$	1.12 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-089
	GMSB ($\tilde{\ell}$ NLSP)	2 e,μ	2-4 jets	Yes	4.7	$\tilde{g}$	1.24 TeV	tanβ<15	1208.4688
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	20.3	$\tilde{g}$	1.6 TeV	tanβ >20	1407.0603
	GGM (bino NLSP)	2 γ	-	Yes	20.3	$\tilde{g}$	1.28 TeV	$m(\tilde{\chi}_1^0)$>50 GeV	ATLAS-CONF-2014-001
	GGM (wino NLSP)	1 e,μ + γ	-	Yes	4.8	$\tilde{g}$	619 GeV	$m(\tilde{\chi}_1^0)$>50 GeV	ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	$\tilde{g}$	900 GeV	$m(\tilde{\chi}_1^0)$>220 GeV	1211.1167
	GGM (higgsino NLSP)	2 e,μ (Z)	0-3 jets	Yes	5.8	$\tilde{g}$	690 GeV	m(NLSP)>200 GeV	ATLAS-CONF-2012-152
	Gravitino LSP	0	mono-jet	Yes	10.5	$F^{1/2}$ scale	645 GeV	$m(\tilde{G})>10^{-4}$ eV	ATLAS-CONF-2012-147
3^{rd} gen. $\tilde{g}$ med.	$\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	$\tilde{g}$	1.25 TeV	$m(\tilde{\chi}_1^0)$<400 GeV	1407.0600
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$	1.1 TeV	$m(\tilde{\chi}_1^0)$ <350 GeV	1308.1841
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$	1.34 TeV	$m(\tilde{\chi}_1^0)$<400 GeV	1407.0600
	$\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$	1.3 TeV	$m(\tilde{\chi}_1^0)$<300 GeV	1407.0600
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{b}_1$	100-620 GeV	$m(\tilde{\chi}_1^0)$<90 GeV	1308.2631
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to t\tilde{\chi}_1^{\pm}$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{b}_1$	275-440 GeV	$m(\tilde{\chi}_1^{\pm})$=2 $m(\tilde{\chi}_1^0)$	1404.2500
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to b\tilde{\chi}_1^{\pm}$	1-2 e,μ	1-2 b	Yes	4.7	$\tilde{t}_1$	110-167 GeV	$m(\tilde{\chi}_1^0)$=55 GeV	1208.4305, 1209.2102
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to Wb\tilde{\chi}_1^0$	2 e,μ	0-2 jets	Yes	20.3	$\tilde{t}_1$	130-210 GeV	$m(\tilde{\chi}_1^0)$ =$m(\tilde{t}_1)$-$m(W)$-50 GeV, $m(\tilde{t}_1)$<<$m(\tilde{\chi}_1^{\pm})$	1403.4853
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to t\tilde{\chi}_1^0$	2 e,μ	2 jets	Yes	20.3	$\tilde{t}_1$	215-530 GeV	$m(\tilde{\chi}_1^0)$=1 GeV	1403.4853
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to b\tilde{\chi}_1^{\pm}$	0	2 b	Yes	20.1	$\tilde{t}_1$	150-580 GeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}_1^{\pm})$-$m(\tilde{\chi}_1^0)$=5 GeV	1308.2631
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	1 e,μ	1 b	Yes	20	$\tilde{t}_1$	210-640 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	1407.0583
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{t}_1$	260-640 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	1406.1122
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$	90-240 GeV	$m(\tilde{t}_1)$-$m(\tilde{\chi}_1^0)$<85 GeV	1407.0608
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_1$	150-580 GeV	$m(\tilde{\chi}_1^0)$>150 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+Z$	3 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_2$	290-600 GeV	$m(\tilde{\chi}_1^0)$<200 GeV	1403.5222
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ	0	Yes	20.3	$\tilde{\ell}$	90-325 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,μ	0	Yes	20.3	$\tilde{\chi}_1^{\pm}$	140-465 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\ell},\tilde{\nu})$=0.5($m(\tilde{\chi}_1^{\pm})$+$m(\tilde{\chi}_1^0)$)	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$	100-350 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\tau},\tilde{\nu})$=0.5($m(\tilde{\chi}_1^{\pm})$+$m(\tilde{\chi}_1^0)$)	1407.0350
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu)$, $\ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	20.3	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$	700 GeV	$m(\tilde{\chi}_1^{\pm})$=$m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})$=0.5($m(\tilde{\chi}_1^{\pm})$+$m(\tilde{\chi}_1^0)$)	1402.7029
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0Z\tilde{\chi}_1^0$	2-3 e,μ	0	Yes	20.3	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$	420 GeV	$m(\tilde{\chi}_1^{\pm})$=$m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled	1403.5294, 1402.7029
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0h\tilde{\chi}_1^0$	1 e,μ	2 b	Yes	20.3	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$	285 GeV	$m(\tilde{\chi}_1^{\pm})$=$m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled	ATLAS-CONF-2013-093
	$\tilde{\chi}_2^0\tilde{\chi}_3^0$, $\tilde{\chi}_{2,3}^0\to\tilde{\ell}_R\ell$	4 e,μ	0	Yes	20.3	$\tilde{\chi}_{2,3}^0$	620 GeV	$m(\tilde{\chi}_2^0)$=$m(\tilde{\chi}_3^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})$=0.5($m(\tilde{\chi}_2^0)$+$m(\tilde{\chi}_1^0)$)	1405.5086
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^{\pm}$	270 GeV	$m(\tilde{\chi}_1^{\pm})$-$m(\tilde{\chi}_1^0)$=160 MeV, $\tau(\tilde{\chi}_1^{\pm})$=0.2 ns	ATLAS-CONF-2013-069
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde{g}$	832 GeV	$m(\tilde{\chi}_1^0)$=100 GeV, 10 μs<$\tau(\tilde{g})$<1000 s	1310.6584
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	15.9	$\tilde{\chi}_1^0$	475 GeV	10<tanβ<50	ATLAS-CONF-2013-058
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	4.7	$\tilde{\chi}_1^0$	230 GeV	0.4<$\tau(\tilde{\chi}_1^0)$<2 ns	1304.6310
	$\tilde{q}\tilde{q}$, $\tilde{\chi}_1^0\to qq\mu$ (RPV)	1 μ, displ. vtx	-	-	20.3	$\tilde{q}$	1.0 TeV	1.5 <$c\tau$<156 mm, BR(μ)=1, $m(\tilde{\chi}_1^0)$=108 GeV	ATLAS-CONF-2013-092
RPV	LFV $pp\to\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\to e+\mu$	2 e,μ	-	-	4.6	$\tilde{\nu}_\tau$	1.61 TeV	λ'_{311}=0.10, λ_{132}=0.05	1212.1272
	LFV $pp\to\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\to e(\mu)+\tau$	1 e,μ + τ	-	-	4.6	$\tilde{\nu}_\tau$	1.1 TeV	λ'_{311}=0.10, $\lambda_{1(2)33}$=0.05	1212.1272
	Bilinear RPV CMSSM	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{q},\tilde{g}$	1.35 TeV	$m(\tilde{q})=m(\tilde{g})$, $c\tau_{LSP}$<1 mm	1404.2500
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	4 e,μ	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$	750 GeV	$m(\tilde{\chi}_1^0)$>0.2×$m(\tilde{\chi}_1^{\pm})$, $\lambda_{121}\neq0$	1405.5086
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to\tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	3 e,μ + τ	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$	450 GeV	$m(\tilde{\chi}_1^0)$>0.2×$m(\tilde{\chi}_1^{\pm})$, $\lambda_{133}\neq0$	1405.5086
	$\tilde{g}\to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$	916 GeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2013-091
	$\tilde{g}\to\tilde{t}_1t$, $\tilde{t}_1\to bs$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{g}$	850 GeV		1404.250
Other	Scalar gluon pair, sgluon→$q\bar{q}$	0	4 jets	-	4.6	sgluon	100-287 GeV	incl. limit from 1110.2693	1210.4826
	Scalar gluon pair, sgluon→$t\bar{t}$	2 e,μ (SS)	2 b	Yes	14.3	sgluon	350-800 GeV		ATLAS-CONF-2013-051
	WIMP interaction (D5, Dirac χ)	0	mono-jet	Yes	10.5	M* scale	704 GeV	$m(\chi)$<80 GeV, limit of<687 GeV for D8	ATLAS-CONF-2012-147

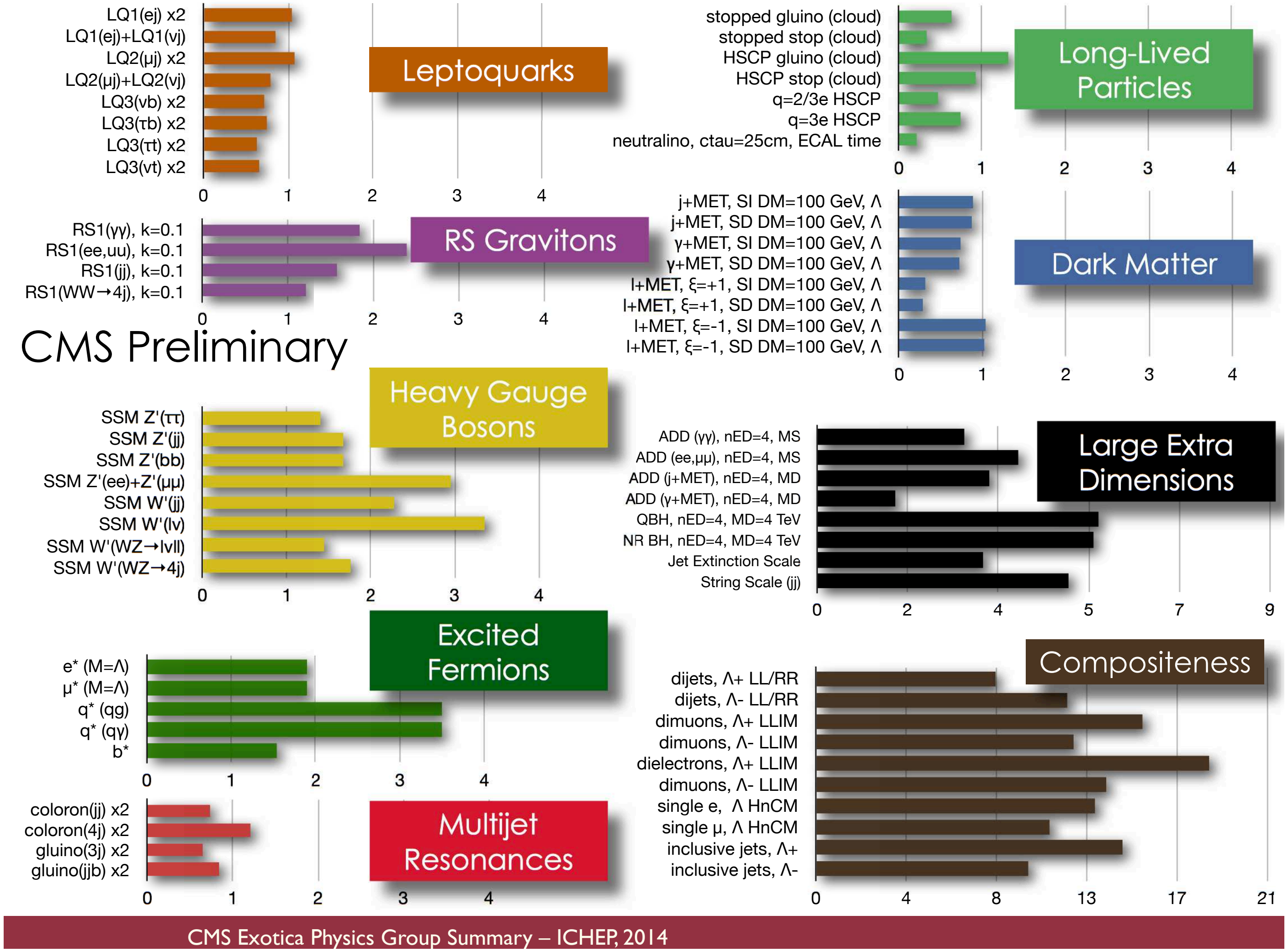
$\sqrt{s}$ = 7 TeV full data

$\sqrt{s}$ = 8 TeV partial data

$\sqrt{s}$ = 8 TeV full data

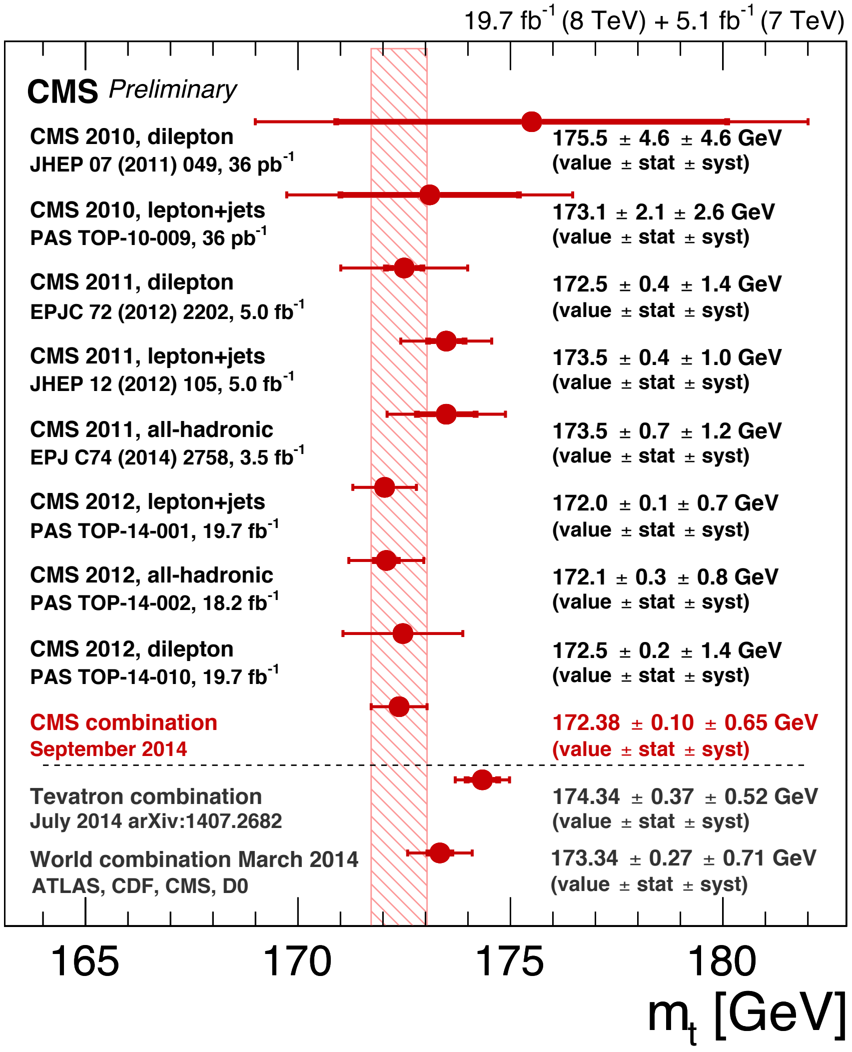
**Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.*

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

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  114 GeV $< m_H <$ 175 GeV

Therefore, we can describe the evolution of the Universe from the very early stages till the present days!

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

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

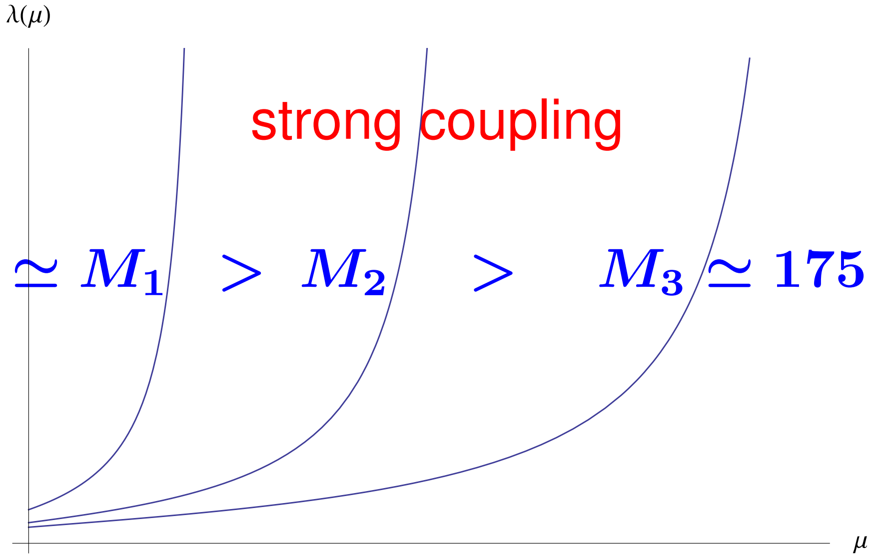
to

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

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.



strong coupling

Higgs mass 1 TeV $\simeq M_1 \;>\; M_2 \;>\; M_3 \simeq 175$ GeV

Fermi Planck

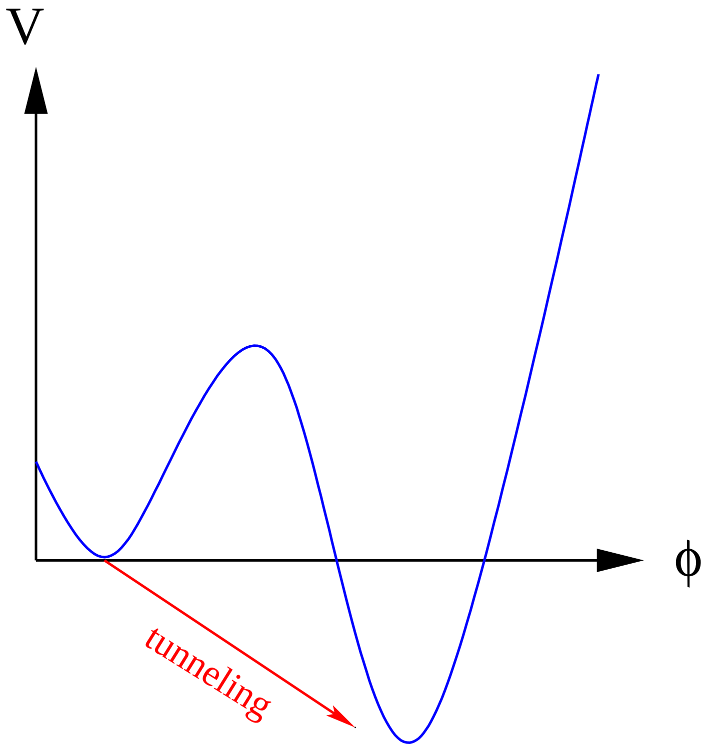
Triviality bound

If $m_H < m_{\max} \simeq 175$ 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

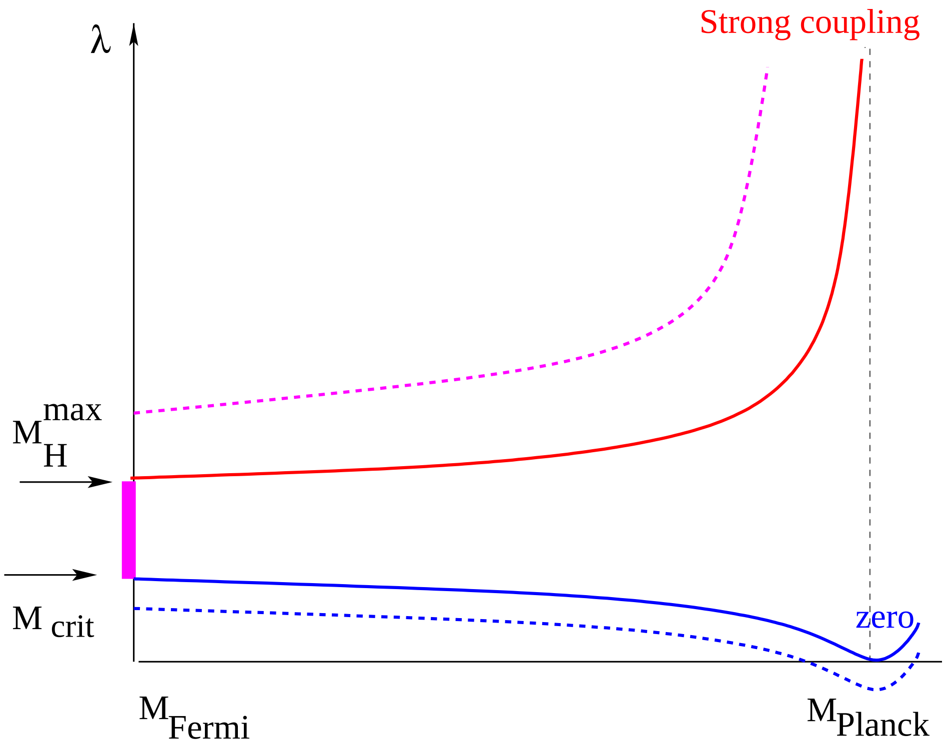
Krasnikov '78, Hung '79; Politzer and Wolfram '79; Altarelli and Isidori '94; Casas, Espinosa and Quiros '94,'96;...; Ellis, Espinosa, Giudice, Hoecker, Riotto '09;...

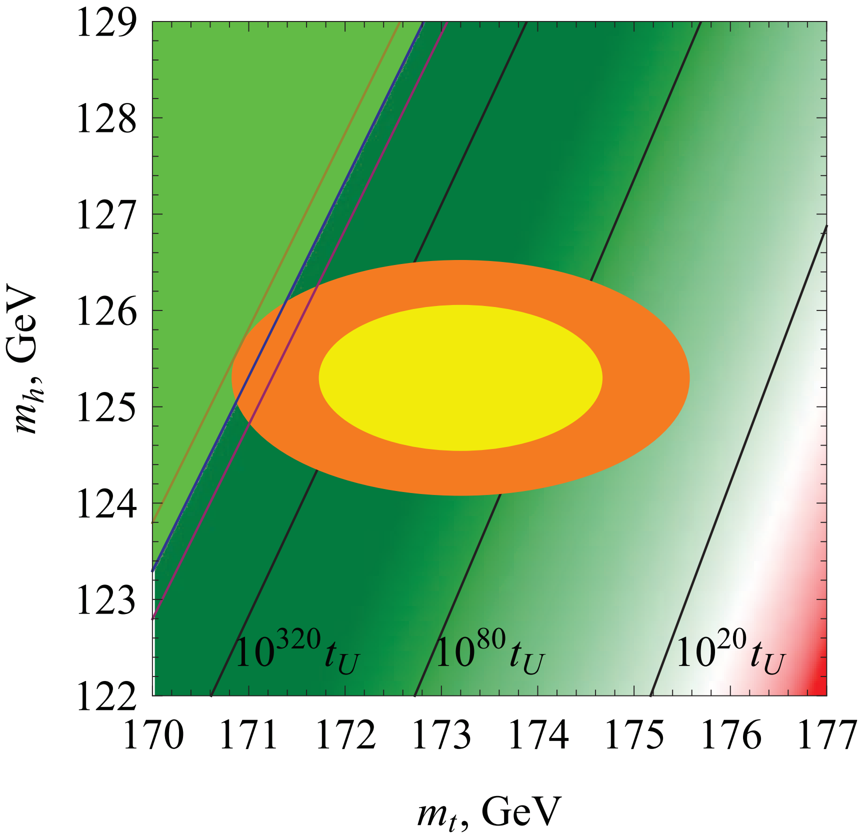


The life-time of our vacuum is smaller than the age of the Universe if $m_H < m_{\mathbf{meta}}$, with $m_{\mathbf{meta}} \simeq \mathbf{111}$ GeV Espinosa, Giudice, Riotto '07

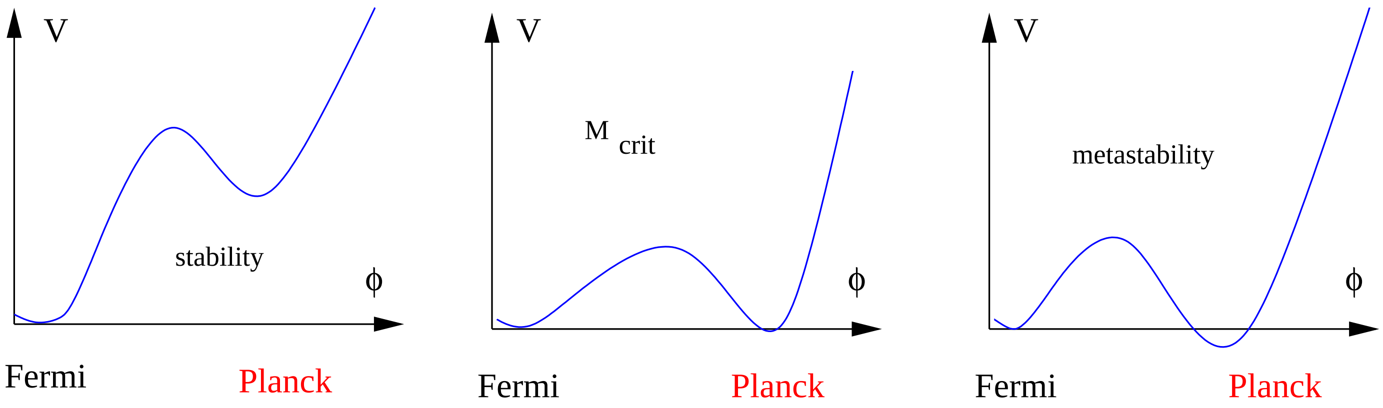
Behaviour of the scalar self-coupling

vacuum lifetime





Important experimental fact 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'):

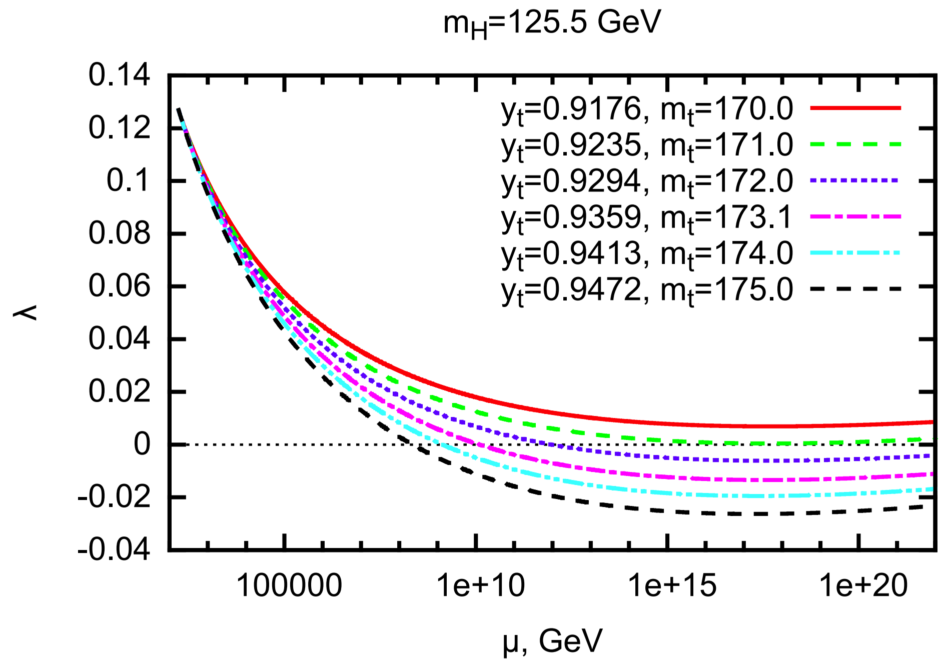


* Froggatt, Nielsen

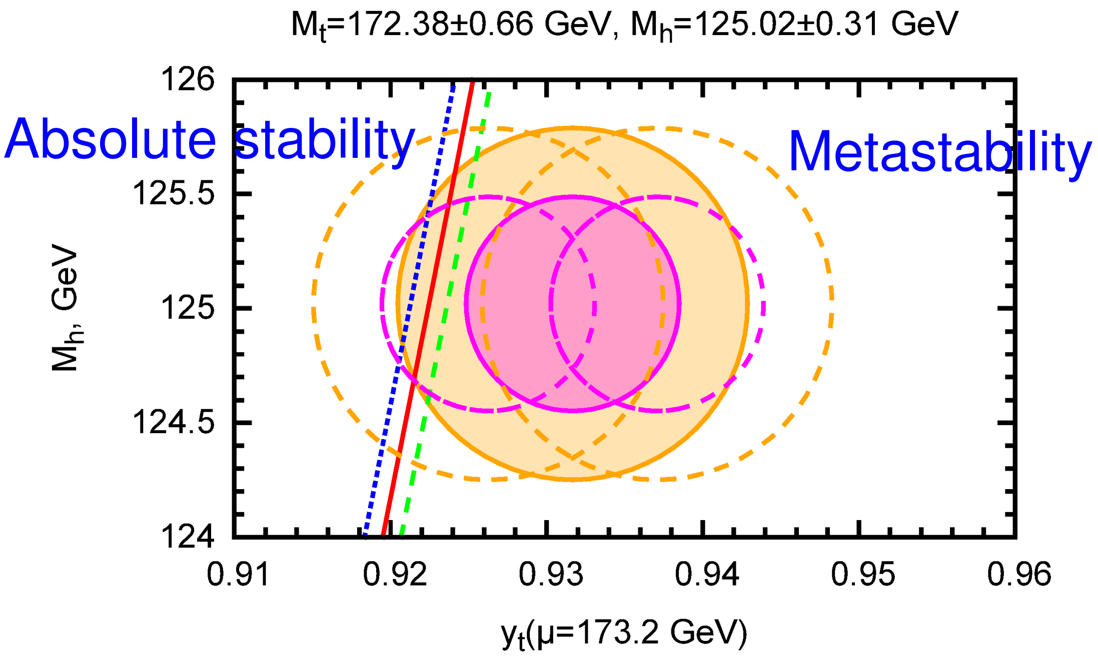
** Bezrukov, MS

De Simone, Hertzberg, Wilczek

*** Wetterich, MS

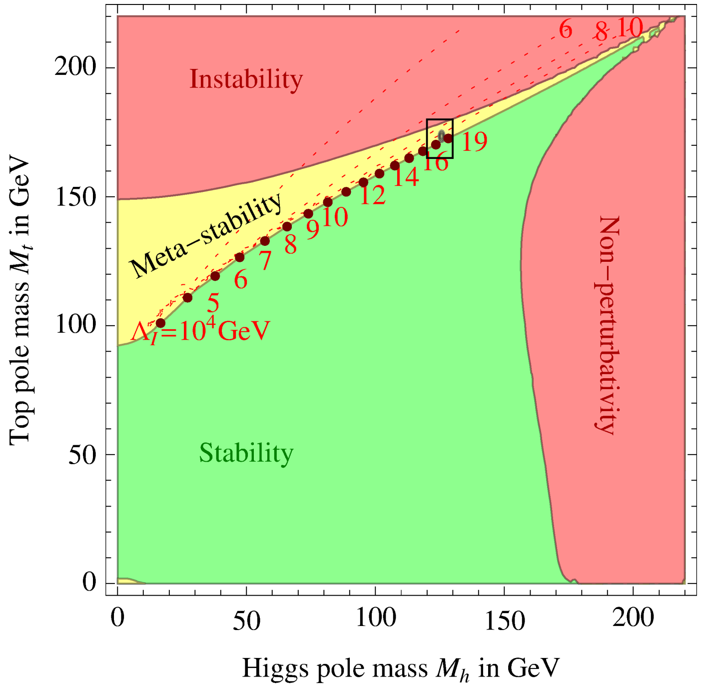


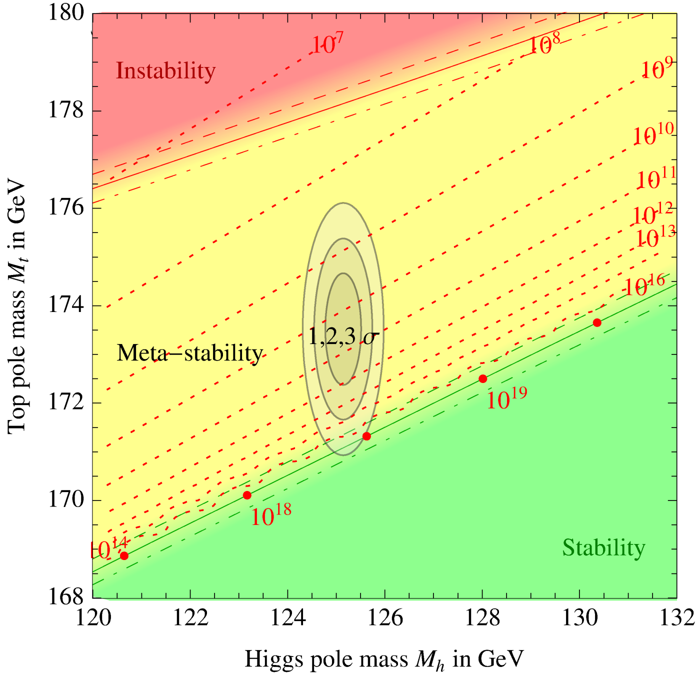
m_H=125.5 GeV



M_t=172.38±0.66 GeV, M_h=125.02±0.31 GeV

Buttazzo et al, ’13, updated in ’14





- The MC mass of the top quark taken ($m_t = 173.34$ GeV) is larger than the latest CMS measurement ($m_t = 172.38$ GeV).
- Systematic uncertainties it relation between the MC mass and the top Yukawa coupling taken ($m_t = 173.34 \pm 0.76_{exp} \pm 0.3_{th}$ GeV) are smaller than the QCD people expect Alekhin et al, Frixione et al.: $\delta m_{th} \simeq 1$ GeV

Higgs Inflation

Higgs coupling to gravity

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,...

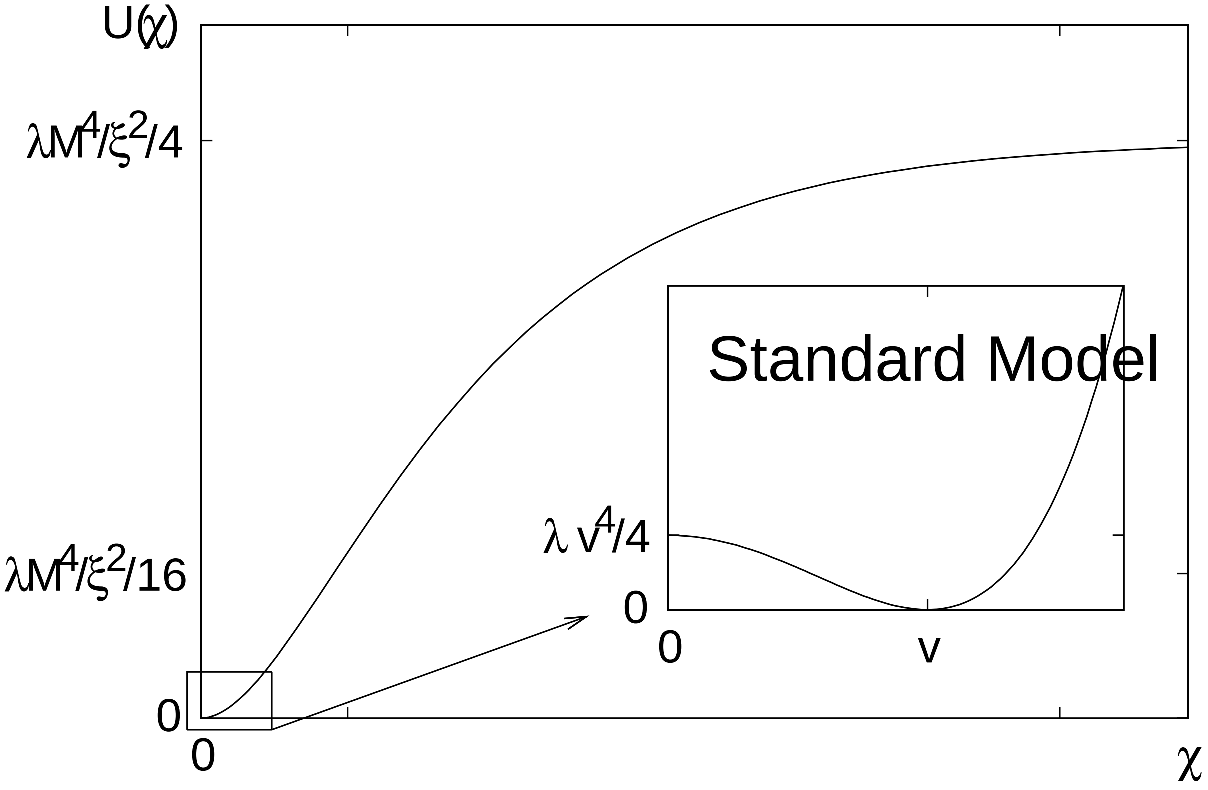
Consider large Higgs fields $h > M_P/\sqrt{\xi}$, which may have existed in the early Universe

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.

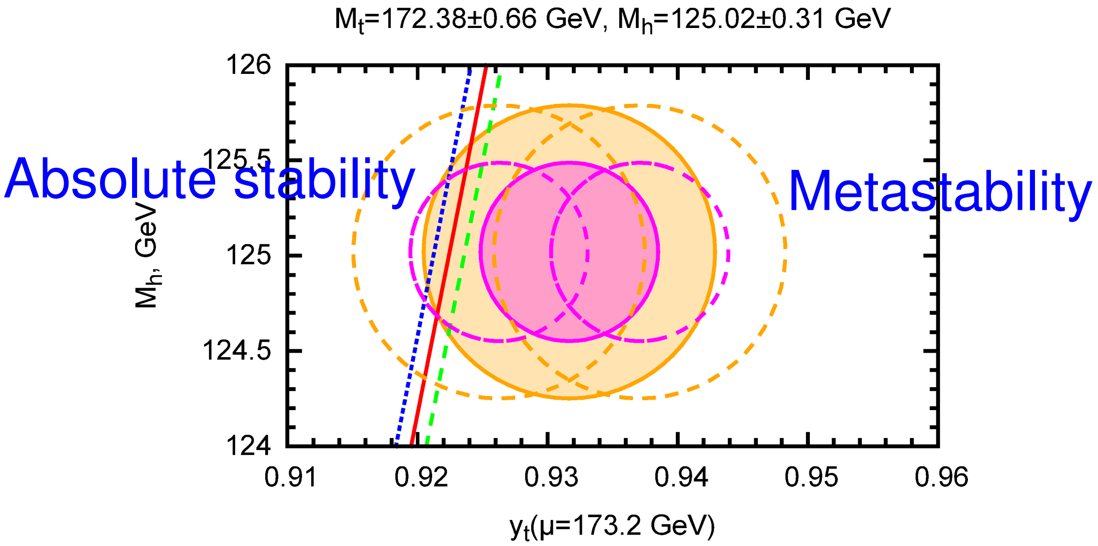
This form of the potential is universal for (Bezrukov, MS) $y_t(173.2) < y_t^{\rm crit}$:

$$y_t^{\rm crit} = 0.9223 + 0.00118\left(\frac{\alpha_s - 0.1184}{0.0007}\right) + 0.00085\left(\frac{M_H - 125.03}{0.3}\right) + 0.0023\left(\frac{\log\xi}{6.9}\right)$$

$y_t(173.2)$ - top Yukawa coupling in $\overline{\rm MS}$- scheme at $\mu = 173.2$ GeV, $\alpha_s(M_Z)$ - strong coupling

theoretical uncertainty: $\delta y_t/y_t \simeq 2\times 10^{-4}$ equivalent to changing of M_H by ~ 70 MeV, or m_t by ~ 35 MeV Buttazzo et al

Numerically for $\xi = 1$, $y_t^{\rm crit}$ coincides with the metastability bound on the top Yukawa coupling

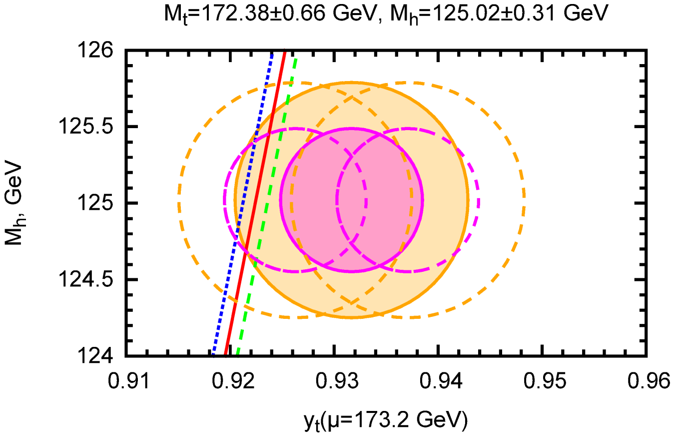


Potential for the Higgs field may be flat at large values of h: Linde chaotic inflation

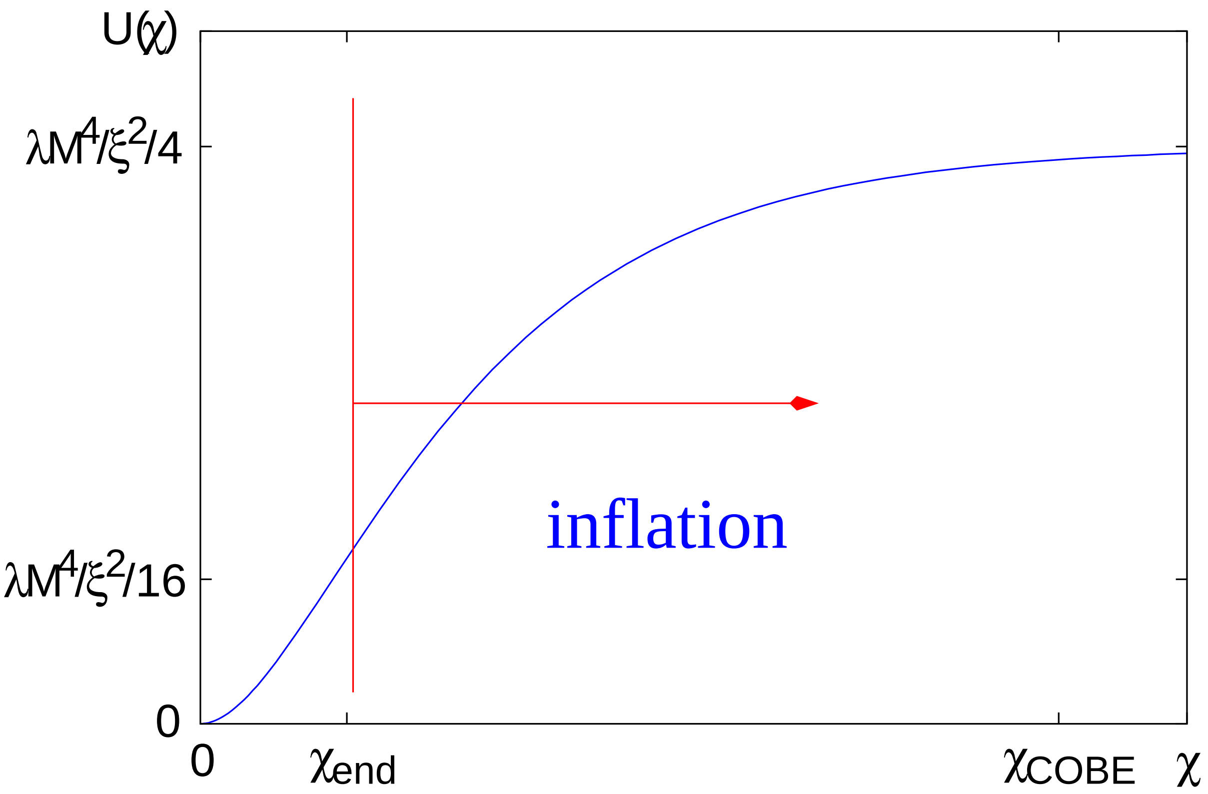
Potential for the Higgs field may be flat at large values of h: Linde chaotic inflation

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

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



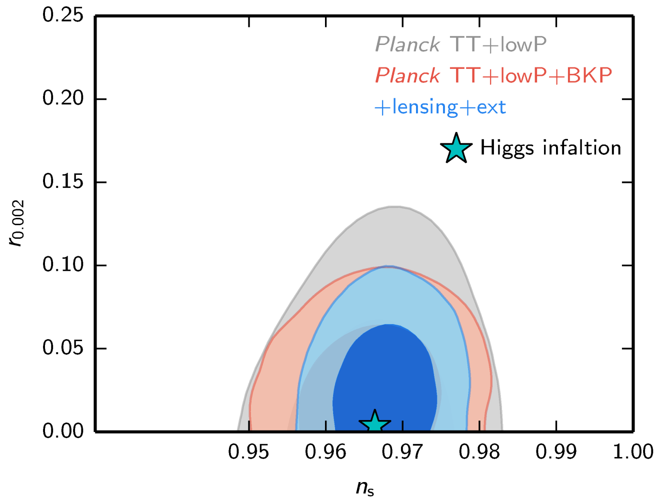
Stage 1: Higgs inflation, $h > \frac{M_P}{\sqrt{\xi}}$, slow roll of the Higgs field

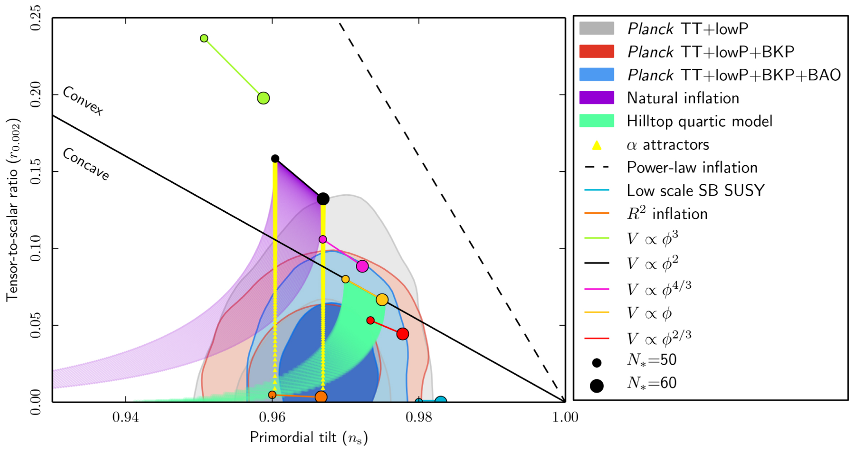


- Makes the Universe flat, homogeneous and isotropic
- Produces fluctuations leading to structure formation: clusters of galaxies, etc

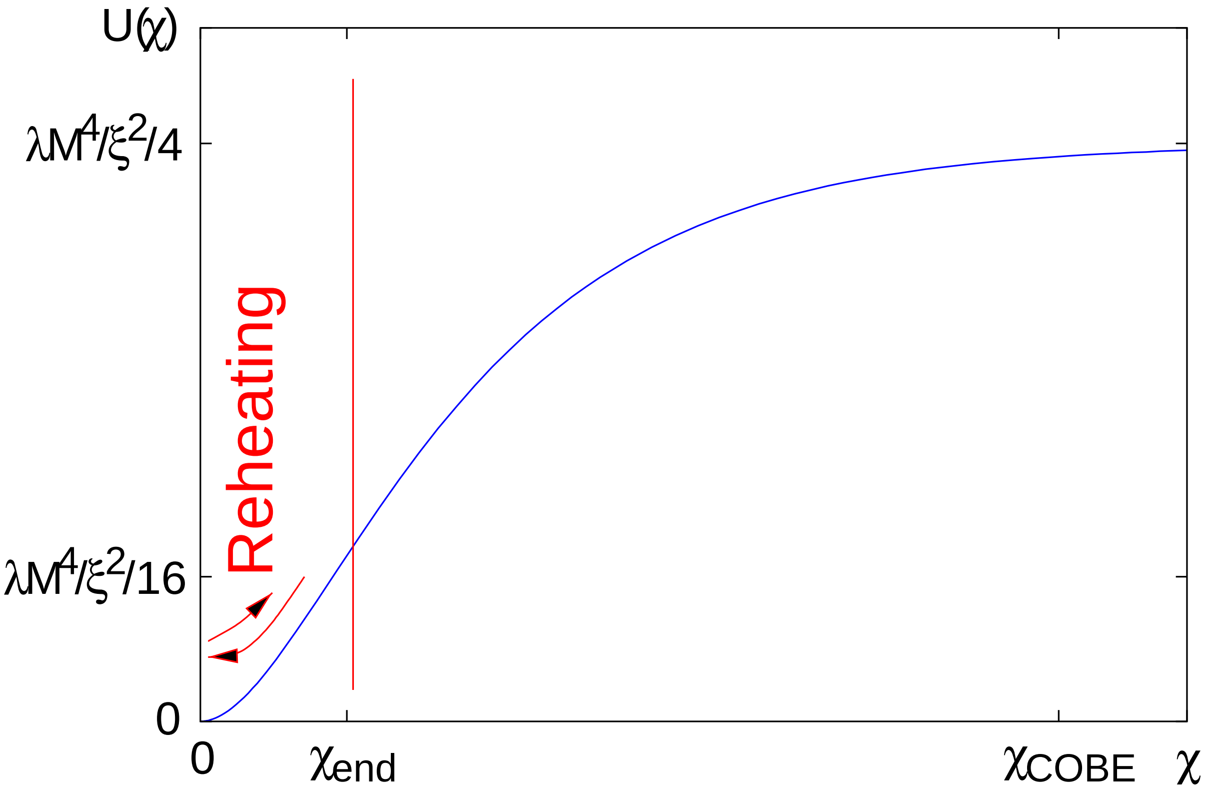
CMB parameters - spectrum and tensor modes, $\xi \gtrsim 1000$

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



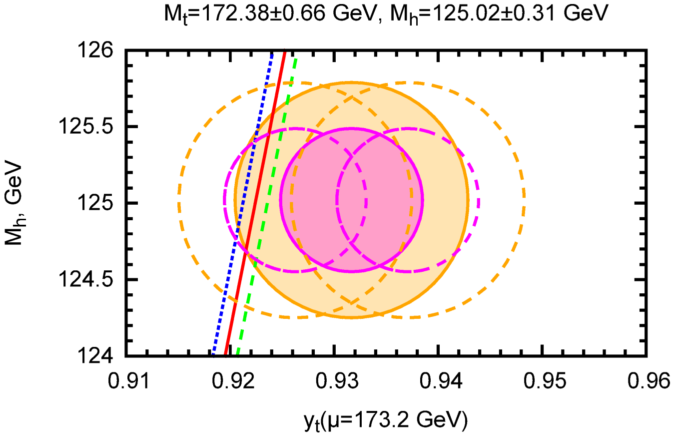


Stage 2: Big Bang, $\frac{M_P}{\xi} < h < \frac{M_P}{\sqrt{\xi}}$, Higgs field oscillations



- 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

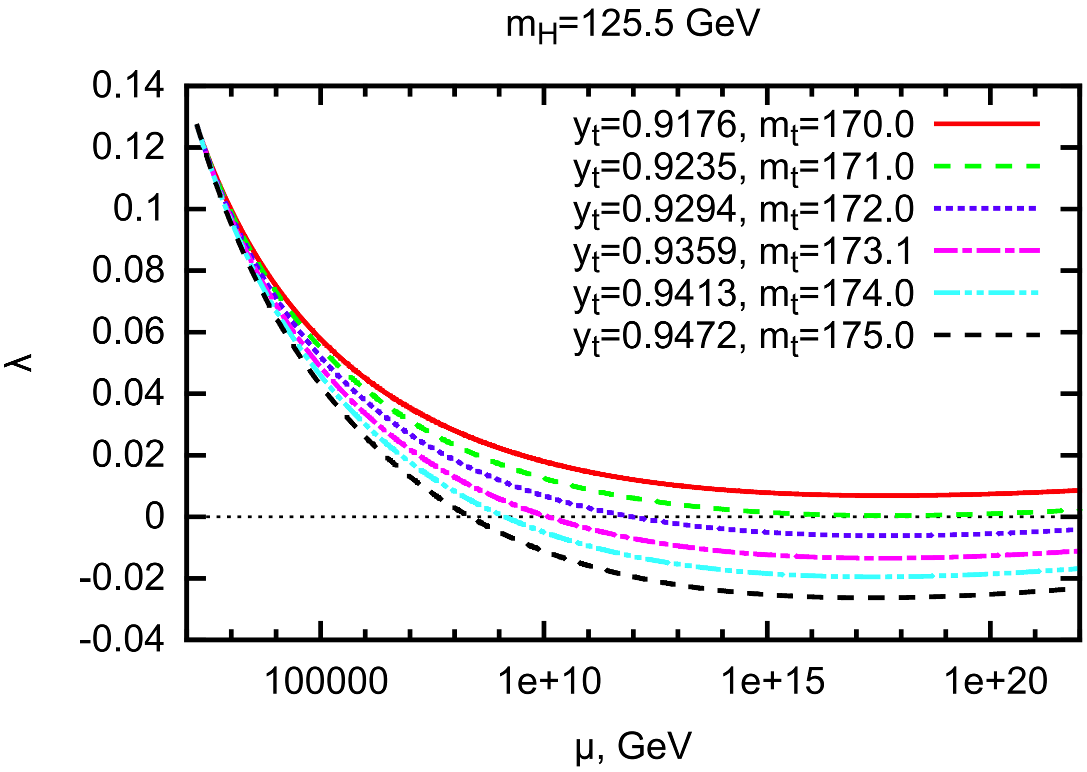
Critical Higgs inflation: $y_t \approx y_t^{\text{crit}}$



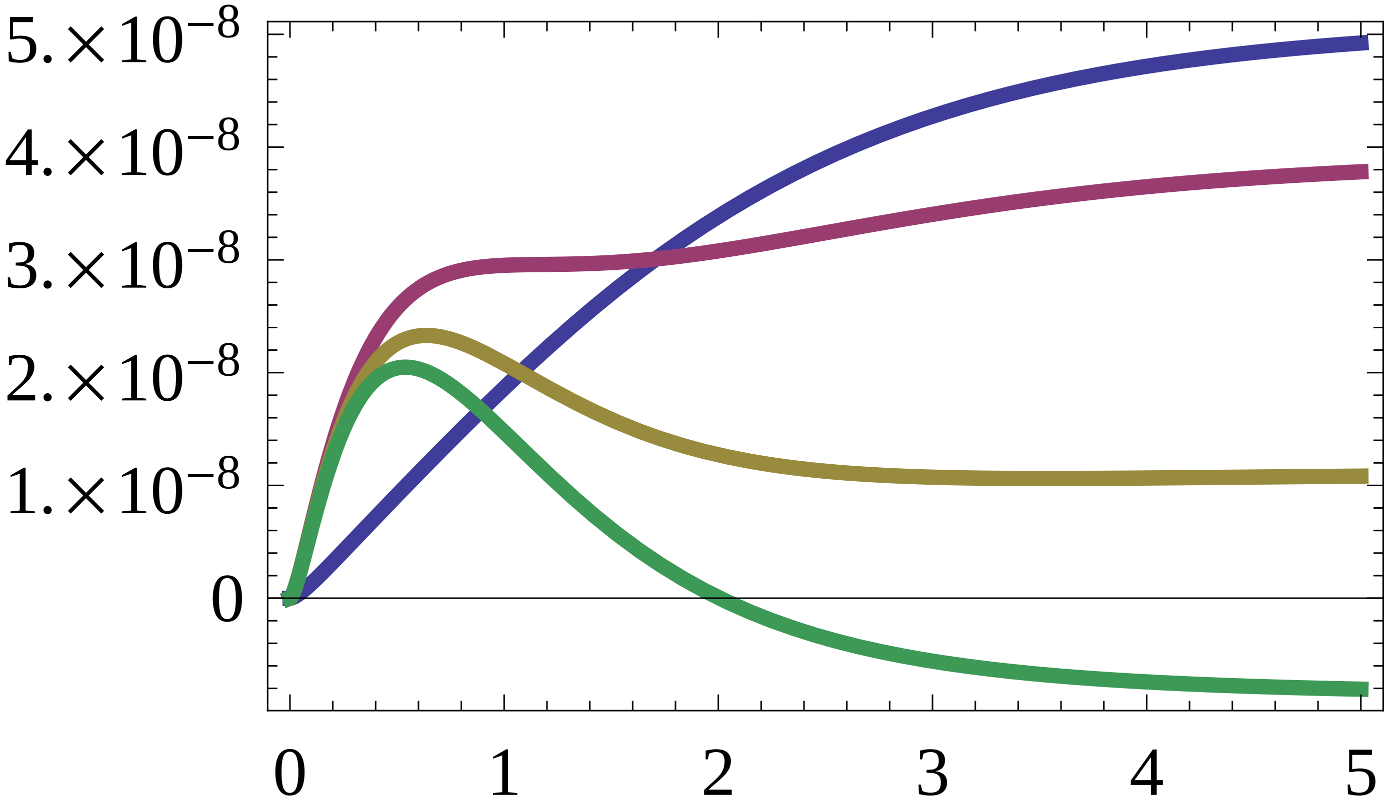
Bezrukov, MS

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

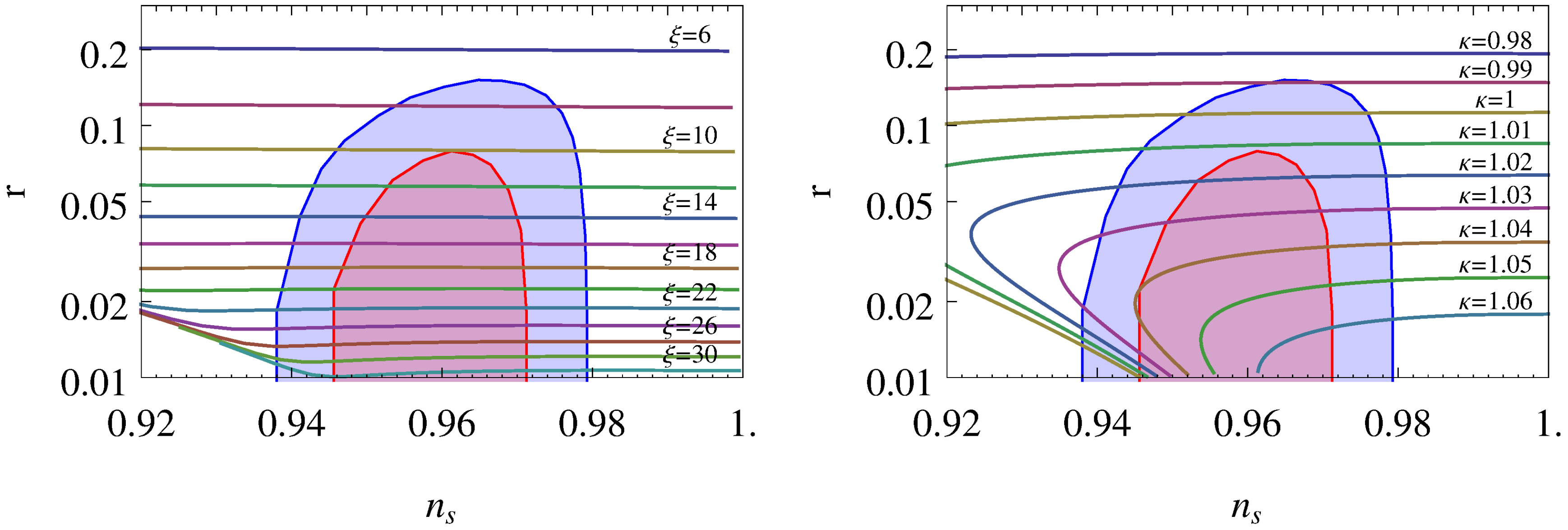
Behaviour of λ:



Effective potential



The inflationary indexes

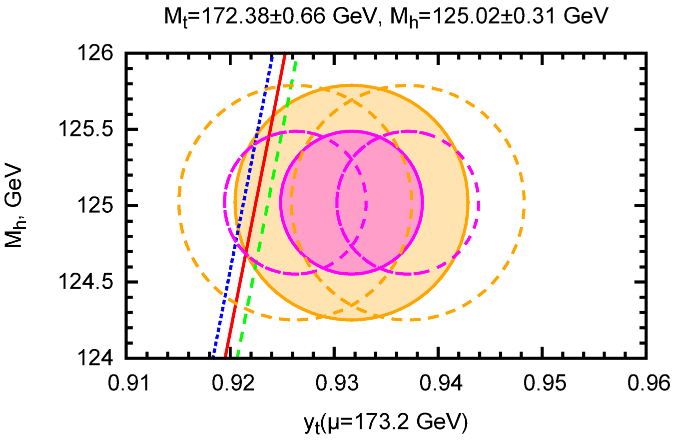


r can be large!

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, $y_t > y_t^{\text{crit}}$

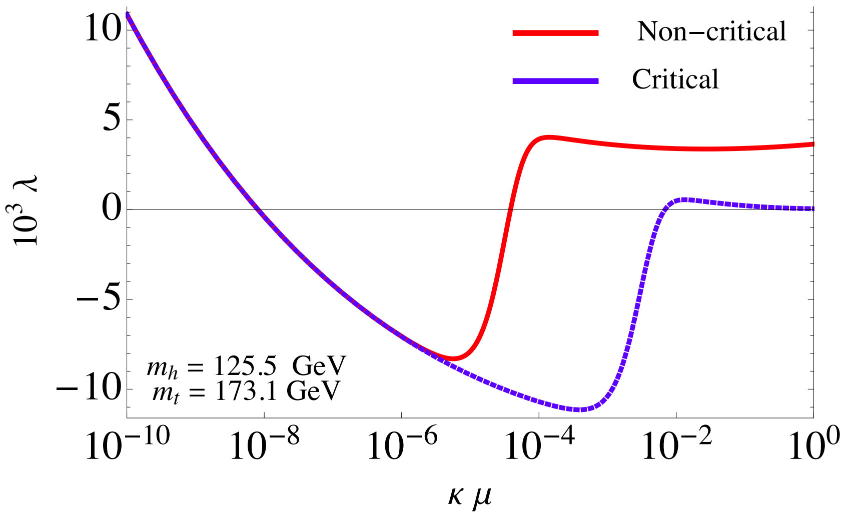


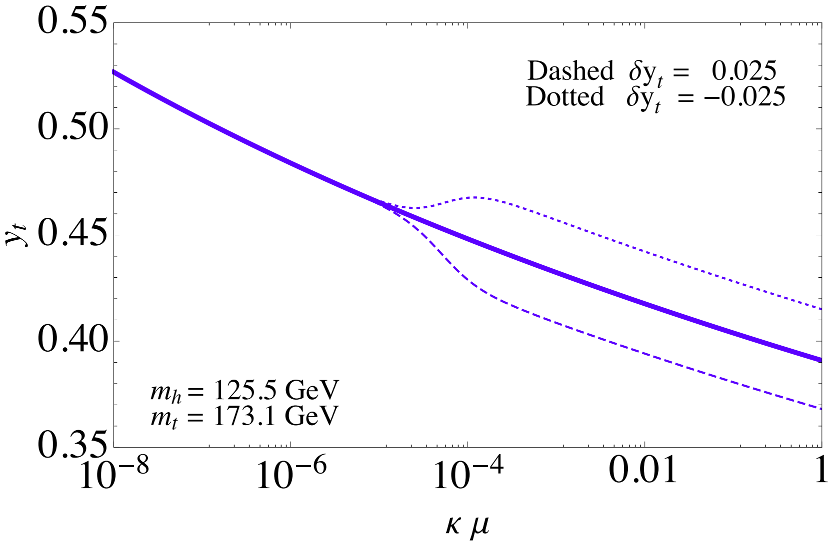
Bezrukov, Rubio, MS

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

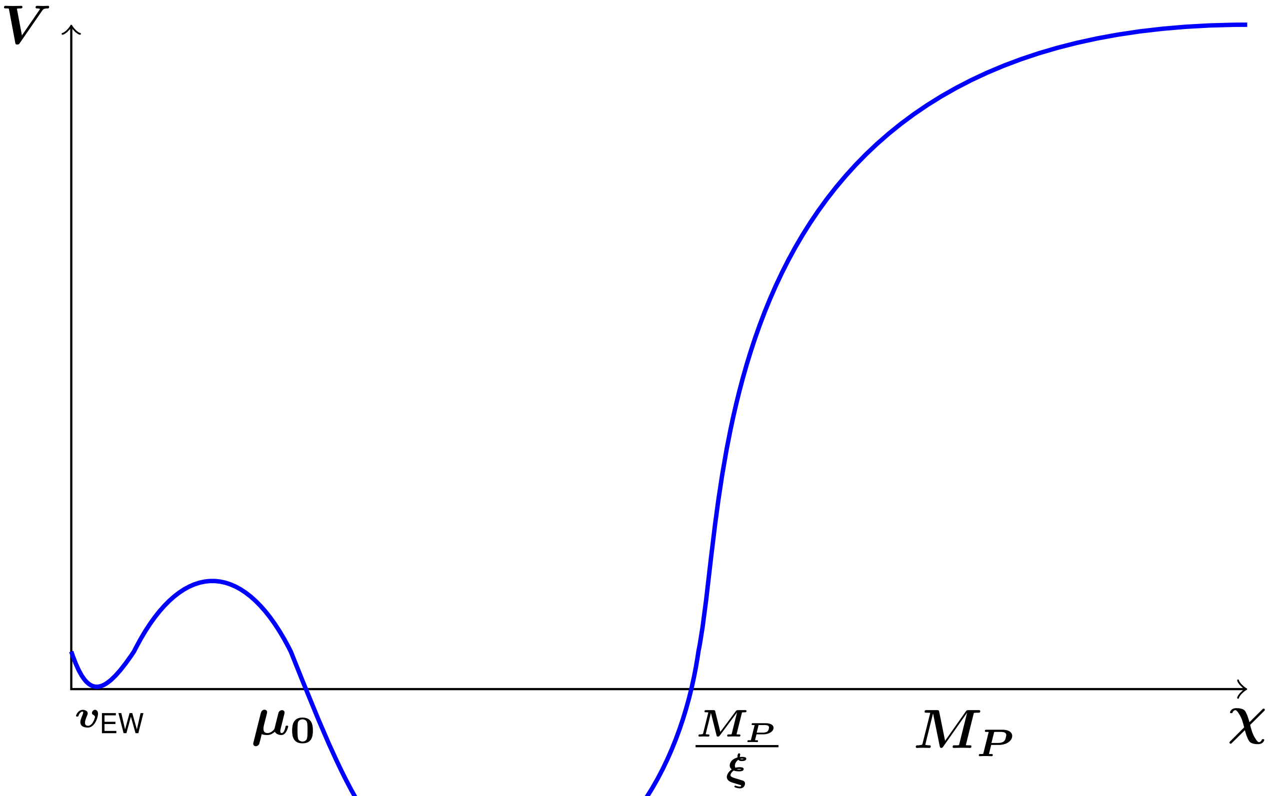
Bezrukov, Magnin, MS., Sibiryakov

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

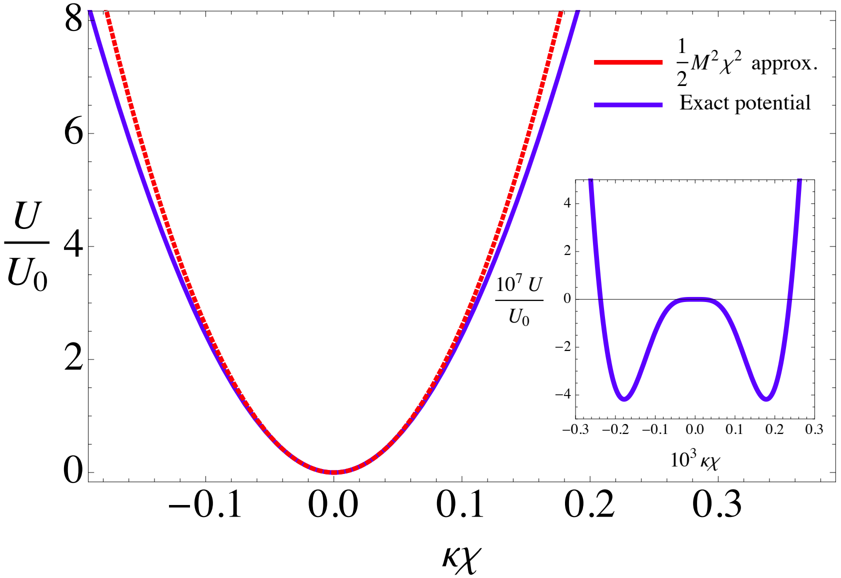


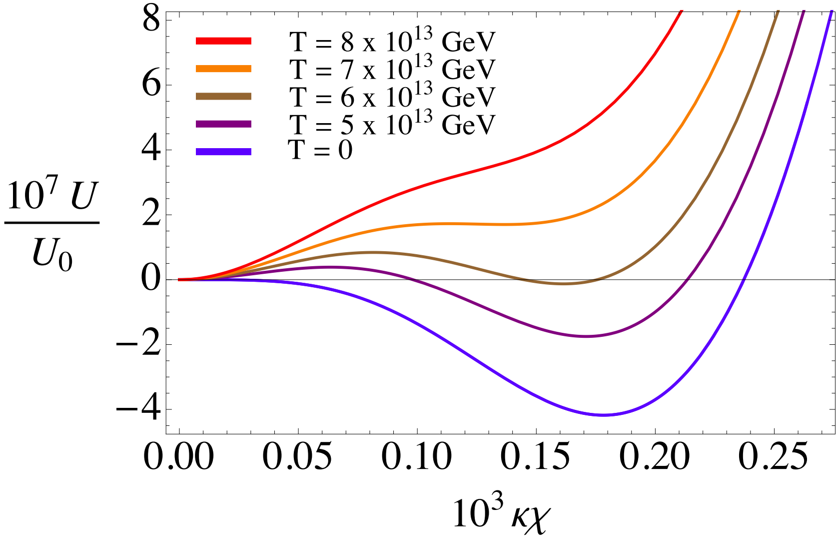


Higgs potential



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

The system is driven to our vacuum and does not go out, as the probability of thermal fluctuations or quantum tunnelling, leading to its decay is extremely small.

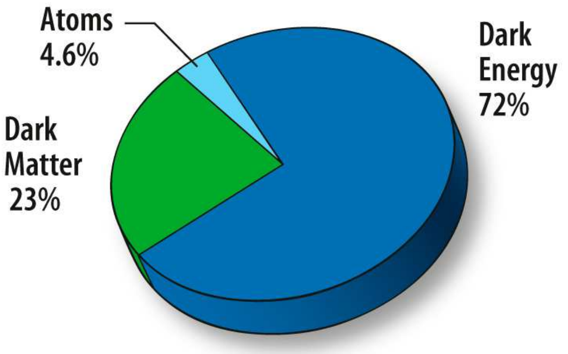
Predictions for critical indexes n_s and r are the same as for non-crtitical Higgs inflation

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

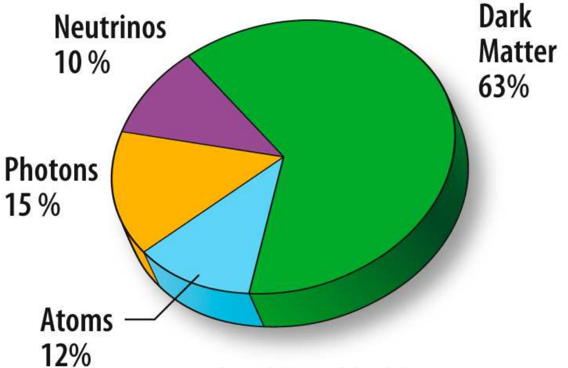
What happens after inflation? We should still get the universe filled with baryons rather than anti-baryons and with Dark matter.

New physics is needed!

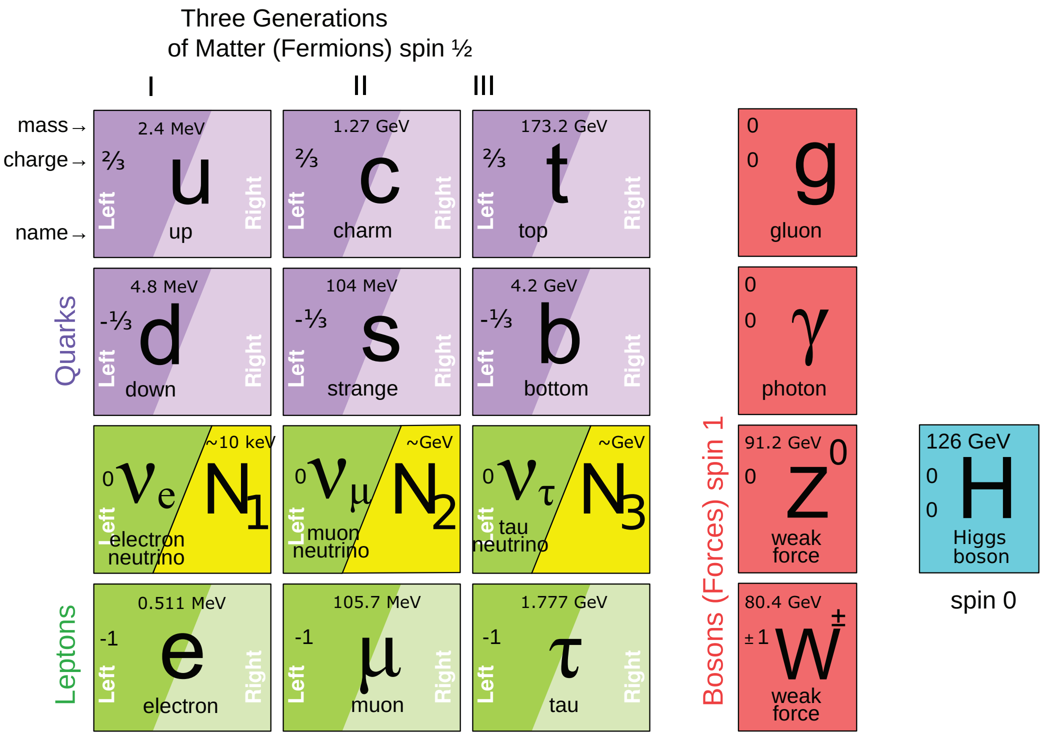
Minimal BSM physics, which can explain simultaneously non-zero neutrino masses, matter-antimatter asymmetry of the Universe and dark matter: the Neutrino Minimal Standard Model - νMSM



TODAY



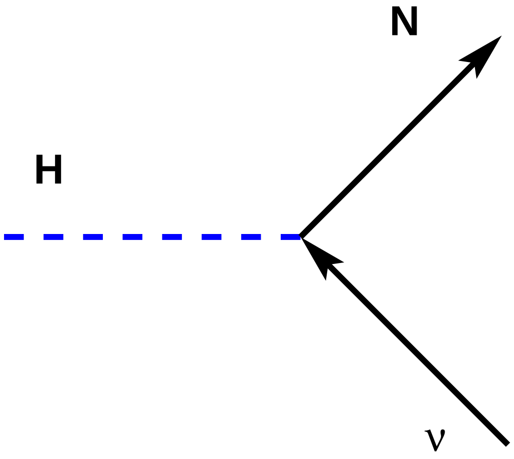
13.7 BILLION YEARS AGO
(Universe 380,000 years old)



Three new particles

- heavy neutral leptons - HNL
- with masses from keV to GeV
- explain in addition neutrino masses and oscillations

Heavy neutral leptons interact with the Higgs boson via Yukawa interactions - exactly in the same way other fermions do:



$$F_{\alpha I}\,\bar{L}_\alpha N_I \tilde{H}$$

These interactions lead to

- active neutrino masses due to GeV scale see-saw
- creation of matter-antimatter asymmetry at temperatures $T \sim 100$ GeV
- to dark matter production at $T \sim 100$ MeV

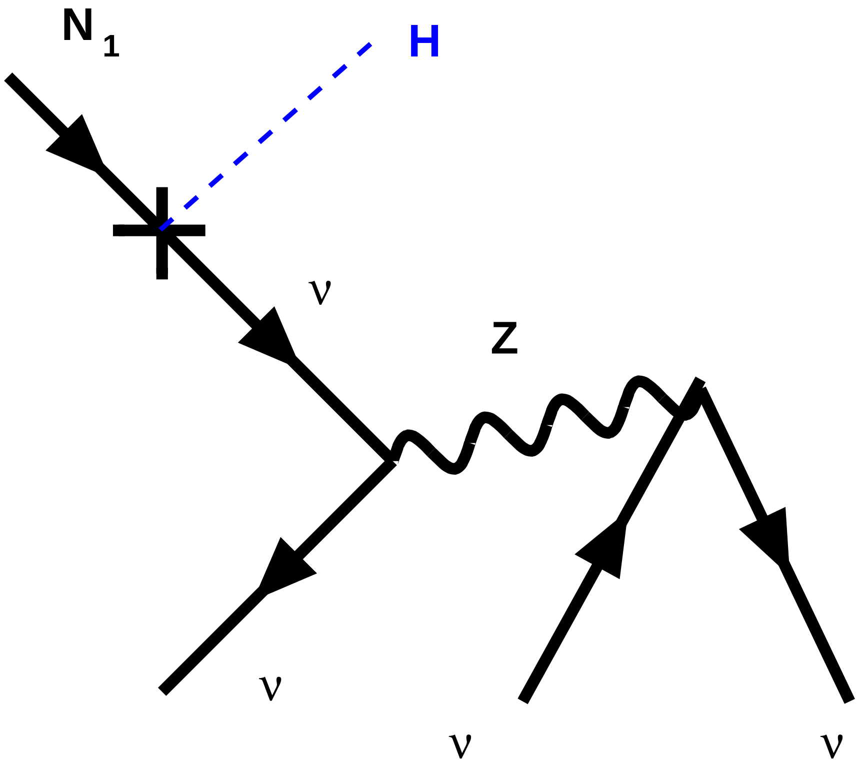
Baryogenesis

- Nothing essentially interesting happens between 10^3 GeV $< T < 10^{13}$ GeV: all SM elementary particles are nearly in thermal equilibrium.
- Heavy neutral leptons $N_{2,3}$ are out of equilibrium. They are created in interaction with the Higgs boson $H \leftrightarrow N\nu,\ \ t\bar{t} \leftrightarrow N\nu$, etc
- CP- violation in these reactions lead to lepton asymmetry of the Universe
- Electroweak baryon number violation due to SM sphalerons convert lepton asymmetry to baryon asymmetry of the Universe
- These processes freeze out at $T \simeq 140$ GeV

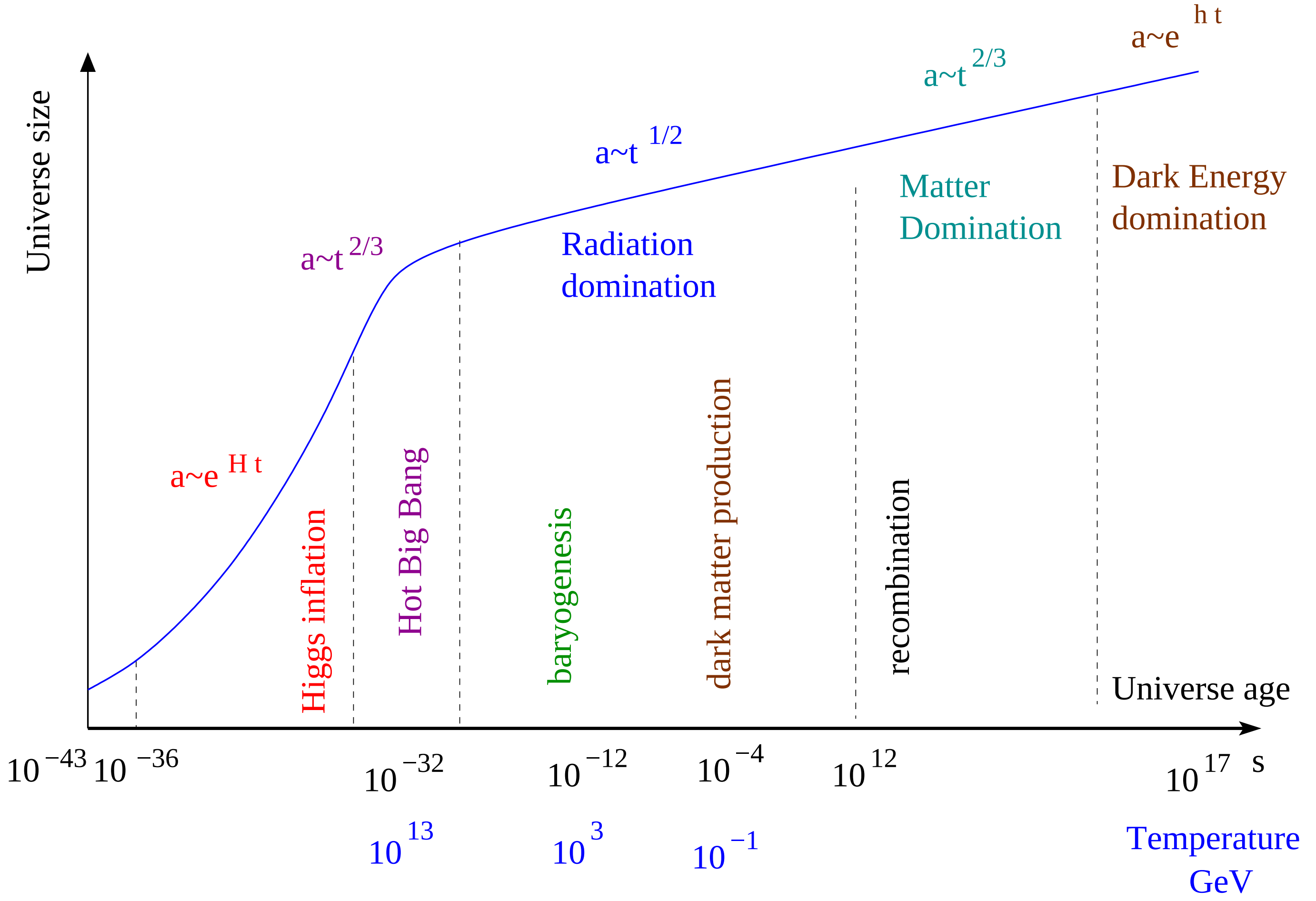
Dark matter production

Production temperature of Dark matter HNL via processes like $l\bar{l} \to \nu N_1$:

$$T \sim 130 \left(\frac{M_I}{1\ \mathrm{keV}} \right)^{1/3}\ \mathrm{MeV}$$

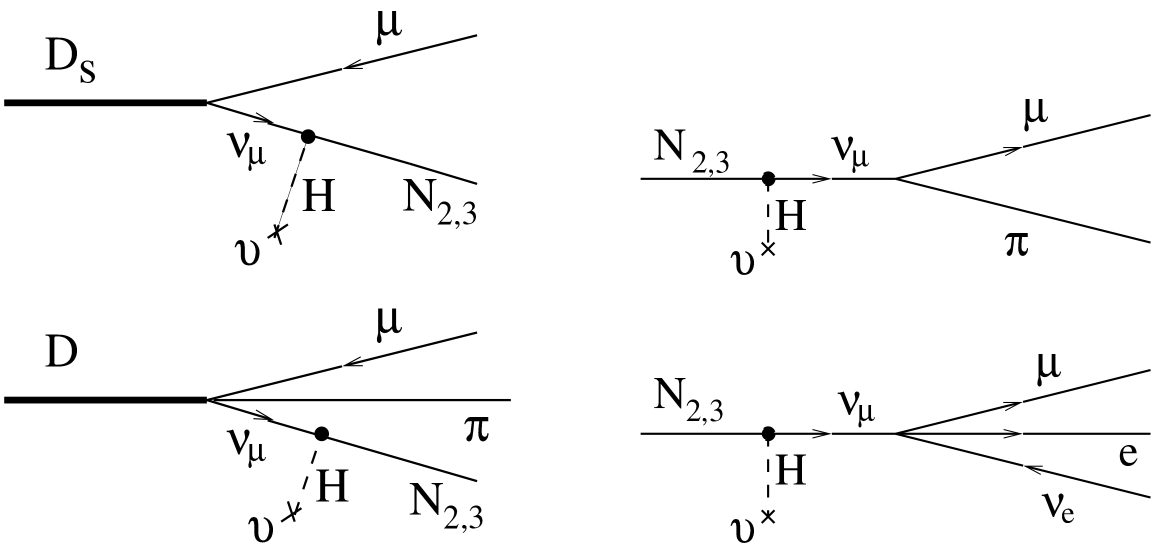


History of the Universe



Experimental search for HNL

- Production
  - via intermediate (hadronic) state $p + \mathbf{target} \rightarrow \mathbf{mesons} + ...$, and then hadron$\rightarrow N + ...$
  - via Z, W-boson decays: $e^+e^- \rightarrow Z \rightarrow \nu N$, $pp \rightarrow W...$, $W \rightarrow lN$
- Detection
  - Subsequent decay of N to SM particles



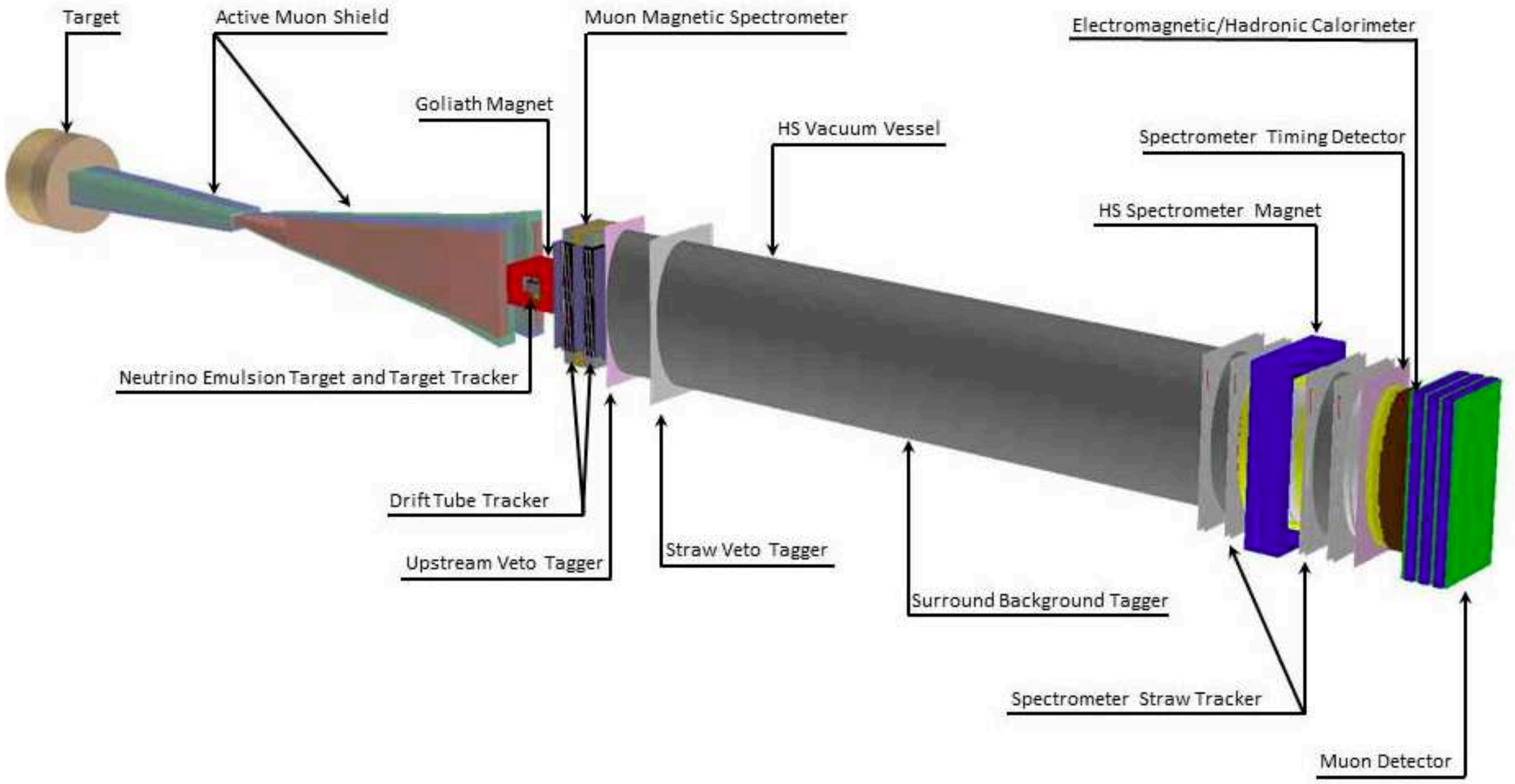
SHiP

Search for Hidden Particles

CERN SPS:

Example of the processes: $pp \to D\bar{D}, \quad D \to N\nu, \quad N \to \pi\mu$

SHiP detector



TLEP, LHC

Processes: $Z \to N\nu, \;\; W \to Nl \; N \to lq\bar{q}$ (lepton + meson, lepton + 2 quark jets),

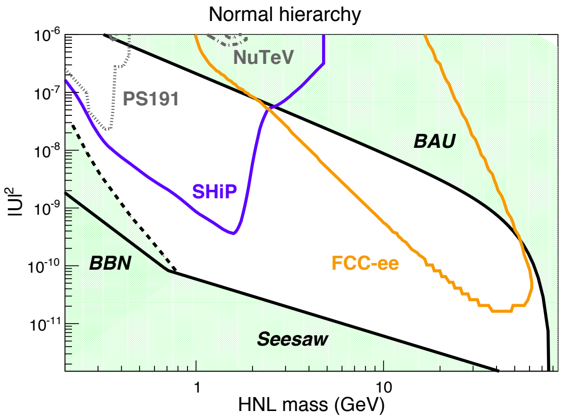
$$BR(Z \to \nu N) \simeq BR(Z \to \nu\nu)U^2, \qquad \Gamma_N \simeq \frac{G_F^2 M^5}{192\pi^3} U^2 A$$

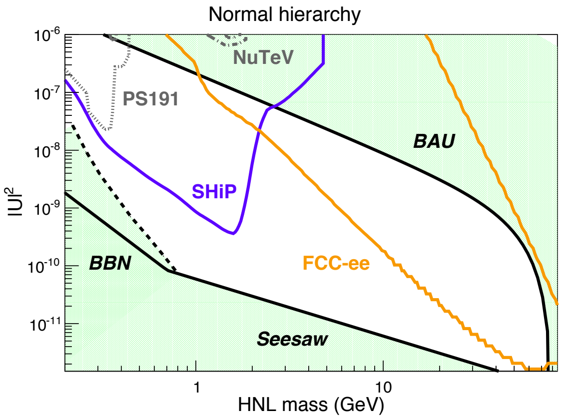
Coefficient A counts the number of open channels, $A \sim 10$ for $M > 10$ GeV

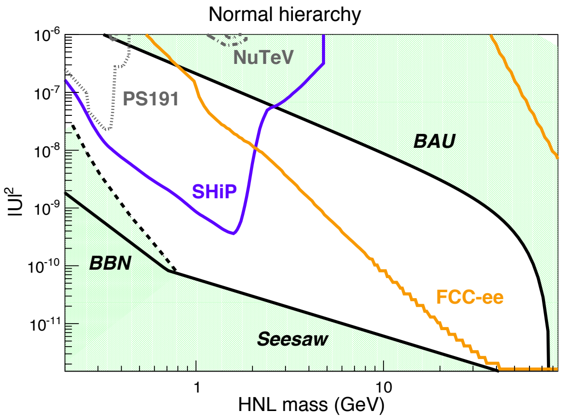
Detector of size L:

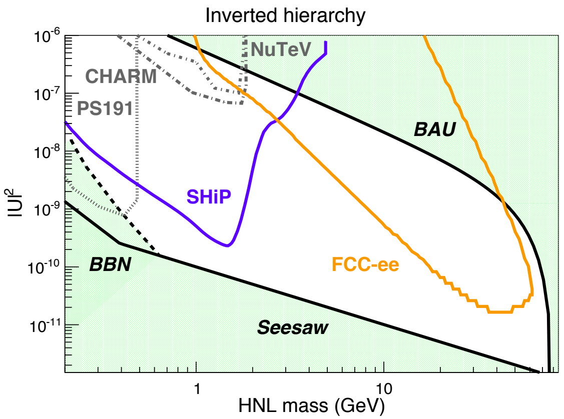
- “short lived” N: decay length < L $\Longrightarrow$ constraint on U^2 may go down to $U^2 < 10^{-10}$ as the sensitivity will grow as the number of Z-decays! This works for $M \gtrsim 20$ GeV.
- “long lived” N: decay length exceeds the size of the detector $\Longrightarrow$ constraint on U^2 may go down to $U^2 < 4 \times 10^{-8}$ as the sensitivity will grow as the square root of the number of Z-decays. This works for lighter HNL.

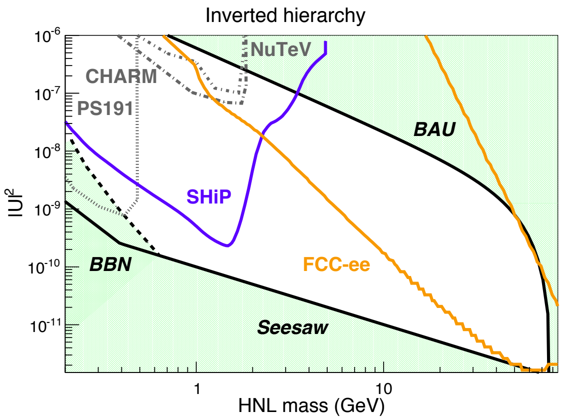
SHiP and FCC-ee sensitivity

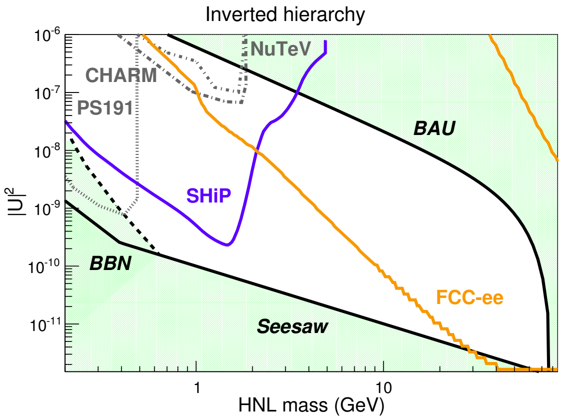












Decay length: 10-100 cm

10-100 cm

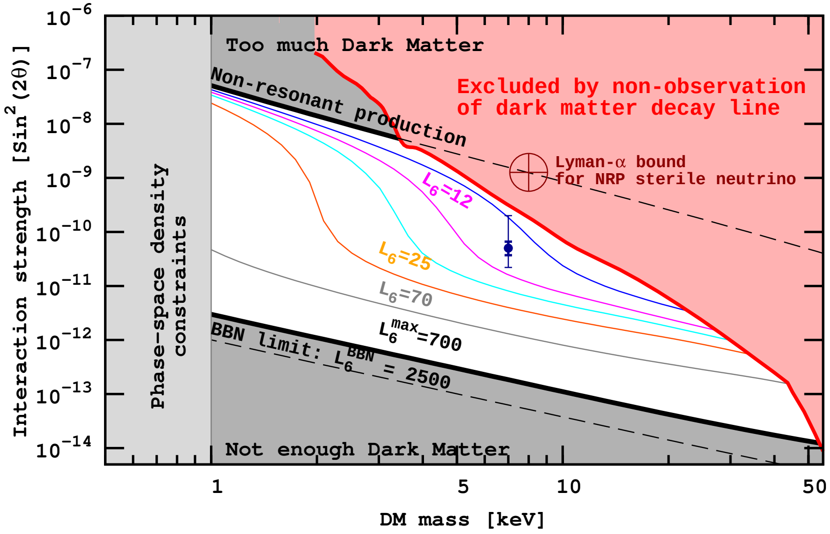
0.01-500 cm

$10^{12}\ Z^0$

$10^{13}\ Z^0$

$10^{13}\ Z^0$

Dark Matter HNL: $N_1 \to \nu\gamma$



Detection of An Unidentified Emission Line in the Stacked X-ray spectrum of Galaxy Clusters. E. Bulbul, M. Markevitch, A. Foster, R. K. Smith, M. Loewenstein, S. W. Randall. e-Print: arXiv:1402.2301

An unidentified line in X-ray spectra of the Andromeda galaxy and Perseus galaxy cluster. A. Boyarsky , O. Ruchayskiy, D. Iakubovskyi, J. Franse. e-Print: arXiv:1402.4119

Conclusions

The Standard Model Higgs field can play an important role in cosmology:

- It can make the Universe flat, homogeneous and isotropic
- Quantum fluctuations of the Higgs field can lead to structure formation
- Coherent oscillations of the Higgs field can make the Hot Big Bang and produce all the matter in the Universe
- Real and virtual Higgs boson can play a crucial role in baryogenesis leading to charge asymmetric Universe
- Dark Matter production may come about as an effect of mixing between neutrinos and heavy neutral leptons, induced by the Higgs field
- A number of new experiments is needed to reveal the “secret” couplings of the Higgs boson