PARTICLE PHYSICS AT THE CROSSROADS

Wilfried Buchmüller

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The Standard Model of Particle Physics has been impressively confirmed by many experiments on strong interactions, electroweak precision tests, flavour and neutrino physics; in extensive searches for 'new physics' no significant deviations from Standard Model predictions were found.

What is the Standard Model of Particle Physics? A relativistic quantum field theory, non-Abelian gauge theory with symmetry group

$$G_{\mathrm{SM}} = SU(3) \times SU(2) \times U(1)$$

for strong and electroweak interactions, and three quark-lepton generations with chiral gauge interactions. The standard model can only be effective low-energy theory, its structure points beyond .... but in which direction .... grand unification, supersymmetry, technicolour, string theory ...?

There is also the Standard Model of Cosmology, based on a gauge theory, Einstein's theory of gravity. During the past decade cosmology has become precision physics, with no deviations from its Standard Model, and many quantitative connections to the Standard Model of Particle Physics.

CURRENT QUESTIONS in Particle Physics include:

- What is the mechanism of electroweak symmetry breaking?
- What is the origin of particle masses and their hierarchy?
- Does the world become supersymmetric at the TeV scale?
- How does matter behave at extremely high energies?
- Is the nature of dark matter related to TeV scale physics?
- Can the Standard Model be embedded in string theory?
- What is the cosmological constant/dark energy?

Which question(s) is (are) most fundamental?

I. The Infrared-Ultraviolet Connection

How far can we extrapolate ($\Lambda_{\rm UV}$) the Standard Model ($\Lambda_{\rm IR}$)? This affects almost all questions: Higgs mechanism, flavour physics, neutrino physics, dark matter, ... In principle, everything is conceivable:

$$\Lambda_{\rm UV} = \Lambda_{\rm IR} \equiv v_{\rm EW} \simeq 300 \text{ GeV} \ldots M_{\rm P} \simeq 10^{18} \text{ GeV} \ .$$

Theoretical studies mostly focus on the two extreme possibilities:

- (A) $\Lambda_{\rm UV} = v_{\rm EW}$: new strong interactions, compositeness (Higgs, quark-lepton and W-boson!), string excitations,... at TeV scale; theoretical motivation: quadratic divergencies for fundamental Higgs scalar

- (B) $\Lambda_{\rm UV} = \Lambda_{\rm GUT}, M_{\rm P}$: elementary Higgs boson, low-energy supersymmetry, perturbative unification, ...; theoretical motivation: quadratic divergencies for fundamental Higgs scalar

$\rightarrow$ Particle Physics at the crossroads; input from LHC will be decisive.

The Higgs Sector

Weak and electromagnetic interactions are described by spontaneously broken gauge theory; Goldstone bosons of symmetry breaking

$$SU(2)_L \times U(1)_Y \rightarrow U(1)_{\rm em}$$

give mass to the W- and Z-bosons via the Higgs mechanism; simplest way realized in Standard Model: vacuum expectation value of single $SU(2)_L$ doublet, i.e. symmetry breaking $SU(2)_L \times SU(2)_R \rightarrow SU(2)_{L+R}$.

Standard Model predicts new elementary particle, the Higgs boson; electroweak precision tests and direct search at LEP:

$$m_H \simeq 87^{+35}_{-26}\ \text{GeV}\ , \quad m_H > 114\ \text{GeV}\ ,$$

further exclusion limits from Tevatron.

So far no Higgs-like boson has been found; many scenarios of electroweak symmetry breaking have been suggested: weakly coupled elementary Higgs bosons with or without supersymmetry, composite Higgs bosons and technicolour, large extra dimensions with no Higgs boson, ...

To identify nature of electroweak symmetry breaking: find (or exclude) 'Higgs-like' resonance, measure mass and spin; study scattering of longitudinally polarized W-bosons at $s \gg m_W^2$ (difficult); gauge boson self-interactions lead to amplitude rising with energy,

$$\mathcal{A}(W_L^a W_L^b \to W_L^c W_L^d) = \mathcal{A}(s)\delta^{ab}\delta^{cd} + \mathcal{A}(t)\delta^{ac}\delta^{bd} + \mathcal{A}(u)\delta^{ad}\delta^{bc} \ ,$$

$$\mathcal{A}(s) = i\frac{s}{v^2} \ ,$$

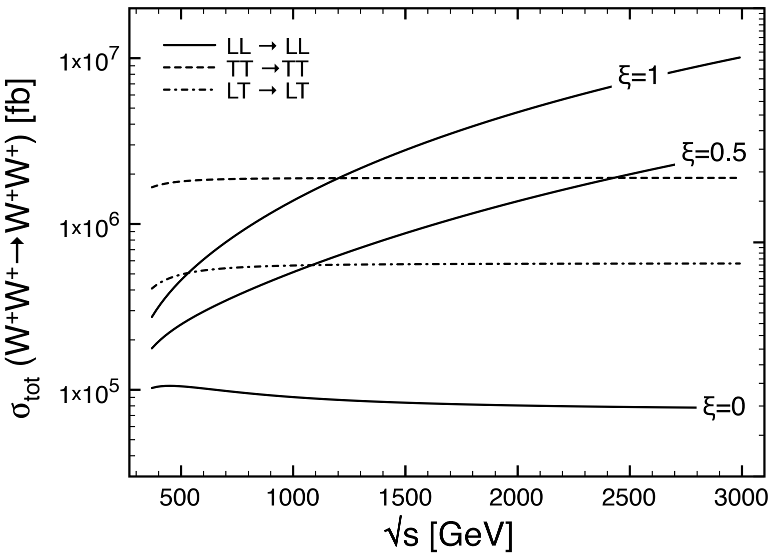
violates unitarity at $\sqrt{s} \simeq 1 - 3\ \mathrm{TeV}$. Additional contribution of scalar field h with coupling α to W-bosons yields scattering amplitude with modified high energy behaviour:

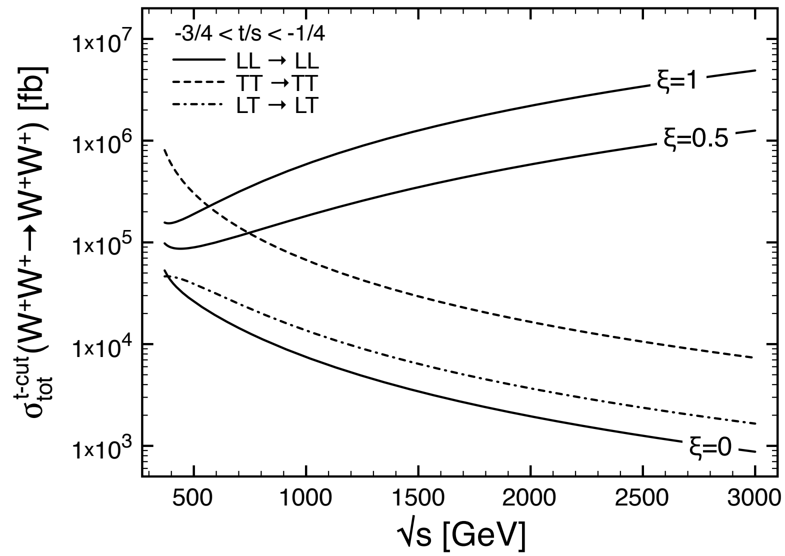
$$\mathcal{A}_{\rm tot}(s) = -i\frac{(\alpha^2-1)s^2 + m_h^2 s}{v^2(s-m_h^2)} \; ;$$

unitarization for $\alpha^2 = 1$ (SM Higgs), or together with contributions from additional states. Example: composite Higgs models with 'light' Higgs compared to compositeness scale $f > v$; restoration of unitarity then at $\sqrt{s} \sim 4\pi f > m_h$, where additional degrees of freedom become visible, related to the strong interactions forming composite Higgs boson.

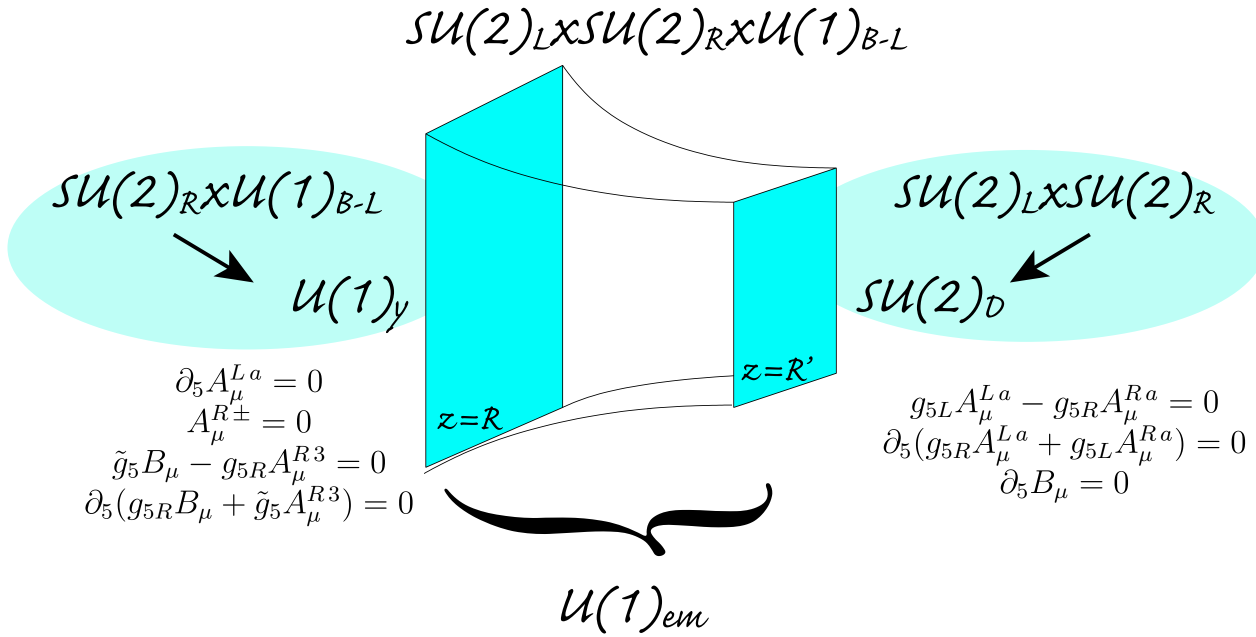
Possible signatures of composite Higgs models can be studied by means of effective Lagrangian ($m_\rho \simeq 4\pi f$, $c_H, c_T \ldots = \mathcal{O}(1)$) (Contino et al. '10),

$$\begin{aligned}\mathcal{L}_{comp} =& \frac{c_H}{2f^2}\left(\partial_\mu\left(H^\dagger H\right)\right)^2 + \frac{c_T}{2f^2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2 - \frac{c_6\lambda}{f^2}\left(H^\dagger H\right)^3 \\ &+ \left(\frac{c_y y_f}{f^2}H^\dagger H \bar{f}_L H f_R + \text{h.c.}\right) + \frac{i c_W g}{2m_\rho^2}\left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H\right)\left(D^\nu W_{\mu\nu}\right)^i + \ldots\end{aligned}$$





$W^+W^+ \to W^+W^+$ partonic cross section as a function of $\sqrt{s}$ for $m_h = 180$ GeV for Standard Model ($\xi = 0$) and for composite Higgs models ($\xi = v^2/f^2 \neq 0$) (Contino et al. '10); note: discovery of 'Higgs boson' at LHC, with no other signs of new physics, still allows rather low scale of compositeness, $\xi \simeq 1$.



Extreme case: warped Higgsless model (Csaki et al. '04); 5D gauge theory in a fixed gravitational anti-de-Sitter (AdS) background; electroweak symmetry breaking by boundary conditions; prediction: no Higgs boson; W- and Z-bosons: Kaluza-Klein modes with mass due to transverse momentum in the extra dimensions,

$$E^2 = \vec{p}_3^{\,2} + p_\perp^2 = \vec{p}_3^{\,2} + m_W^2 \ ,$$

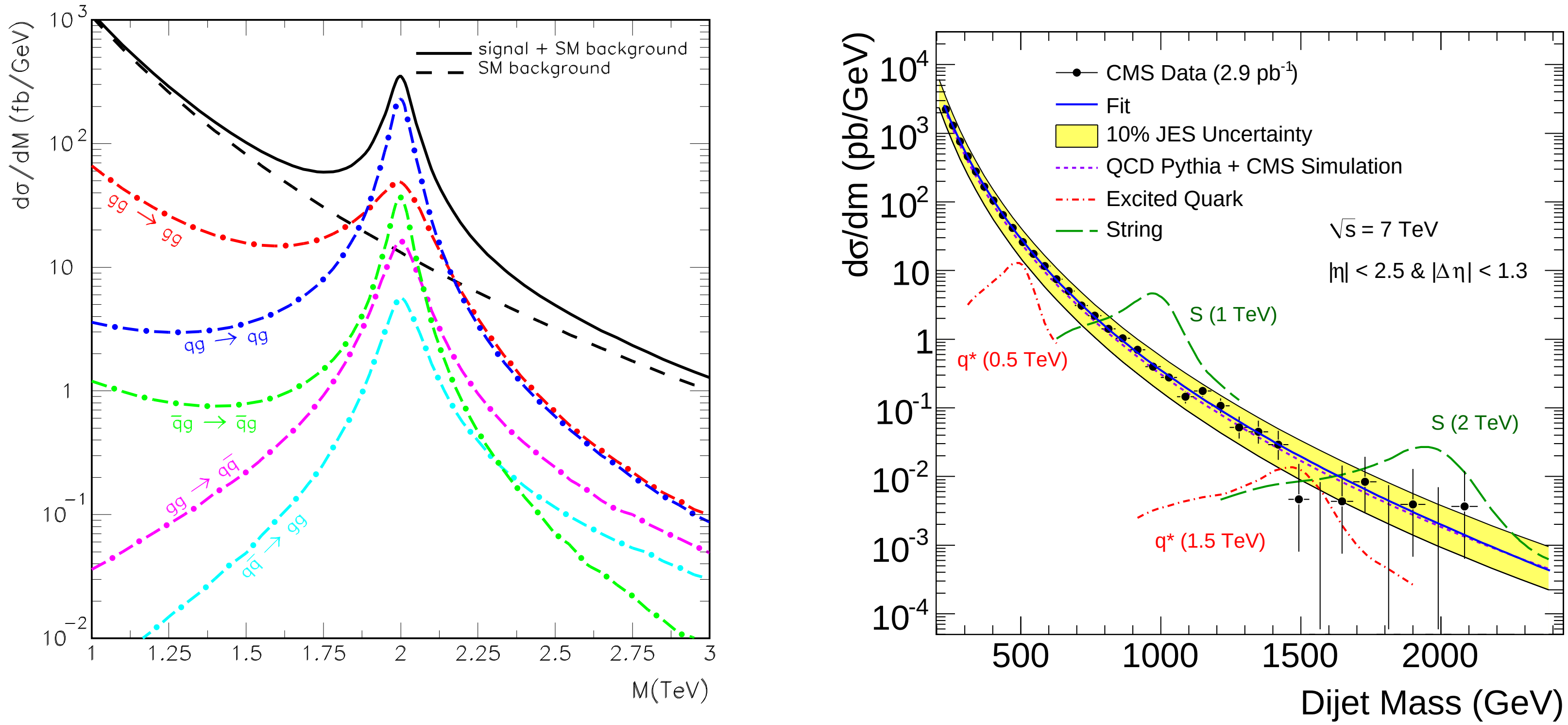
with $\vec{p}_3$ ordinary 3-momentum; prediction of exited states:

$$M_{W'} \sim M_{Z'} \sim M_{\gamma'} \sim 1.2 \text{ TeV} \ .$$

Excited states lead to unitarization of WW scattering amplitude,

$$\mathcal{A} = \mathcal{A}^{(4)} \left(\frac{\sqrt{s}}{v}\right)^4 + \mathcal{A}^{(2)} \left(\frac{\sqrt{s}}{v}\right)^2 + \mathcal{A}^{(0)} + \dots$$

Sum over all Kaluza-Klein modes implies $\mathcal{A}^{(4)} = \mathcal{A}^{(2)} = 0$, consequence of relations between couplings and masses enforced by the higher-dimensional gauge theory.



Most spectacular: TeV scale string theory, quantum gravity at the LHC, Regge excitation of everything: quarks, leptons, gluons, Higgs, ...; already strongly constrained by data; *left*: string prediction (Anchordoqui et al. '08), *right*: current CMS bound, $M_{\text{Regge}} > 2.5$ TeV.

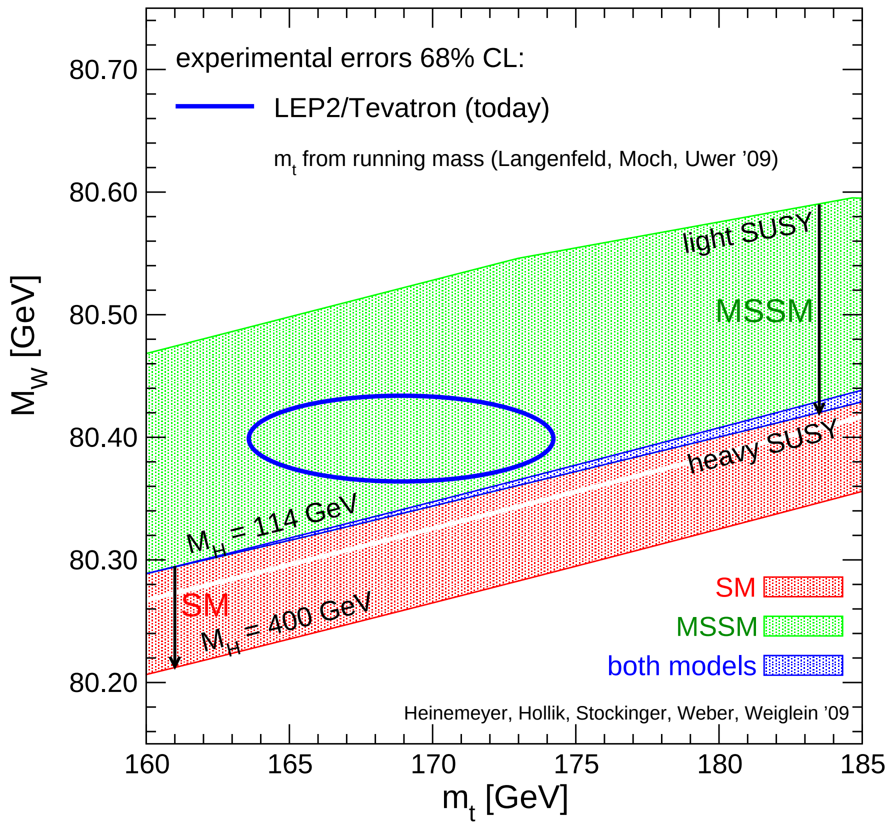
The Top-Higgs System

In the Standard Model the top-quark is special because of its large Yukawa coupling; in some supersymmetric models, the top even triggers electroweak symmetry breaking. Very remarkable: top-quark mass is now known an accuracy comparable to width (CDF/D0 '09),

$$m_{\rm top} = 173.1 \pm 1.3 \text{ GeV} \ .$$

Can we directly measure the total width? Are there decay channels beyond those predicted by the Standard Model?

The top-Higgs system plays special role in many extensions of the Standard Model: composite models, grand unified models, string compactifications, ...; it is conceivable that departures from Standard Model become first visible in the top-Higgs system.



Electroweak parameter fits 'favour' the supersymmetric standard model over the Standard Model; strong dependence on the top mass! Intriguing hint for light superparticle mass spectrum!

Flavour Physics

CKM description of flavour mixing and in CP violation is remarkably successful (Unitarity Triangle fits!). So far no significant deviation from Standard Model detected. Naive operator analysis from electroweak precision tests and data on flavour changing neutral currents (FCNC) yields lower bounds on 'new physics' (Buras '09):

$$\Lambda_{\text{NP}}^{\text{EW}} > 5 \text{ TeV} , \quad \Lambda_{\text{NP}}^{\text{FCNC}} > 1000 \text{ TeV} .$$

Details very model dependent; some models, e.g. Randall-Sundrum models, 'Littlest Higgs' model, low-energy supersymmetric models, ..., predict FCNC's to be discovered soon.

Important part of flavour physics: neutrino masses and mixings; naive expectation: GUT scale physics (seesaw, leptogenesis); however, TeV scale neutrino physics also conceivable; interpretation of neutrino data requires theoretical framework.

Extrapolation to GUT/Planck Scale

Symmetries and particle content of Standard Model together with gauge coupling unification point towards grand unified theories (GUTs). Remarkably, one generation of matter, including right-handed neutrino, forms single spinor representation of $SO(10)$; suggests underlying $SO(10)$ structure of the theory. Route of unification continues via exceptional groups, terminating at E_8,

$$SU(3) \times SU(2) \times U(1) \subset SU(5) \subset SO(10) \subset E_6 \subset E_7 \subset E_8 \ ,$$

usually accompanied by supersymmetry and extra dimensions.

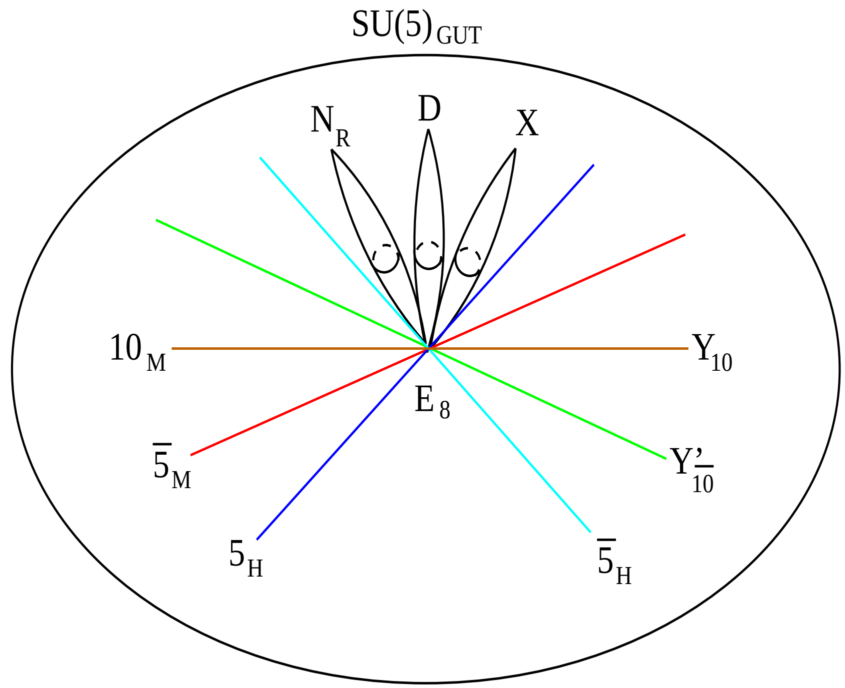
Right-handed neutrino, predicted by $SO(10)$ unification, yields successful phenomenology of neutrino masses and mixings via seesaw mechanism and can account for the cosmological matter-antimatter asymmetry via leptogenesis.

	R	W	B	G	P
u	+	-	-	+	-
u	-	+	-	+	-
u	-	-	+	+	-
d	+	-	-	-	+
d	-	+	-	-	+
d	-	-	+	-	+
u^c	-	+	+	-	-
u^c	+	-	+	-	-
u^c	+	+	-	-	-
d^c	-	+	+	+	+
d^c	+	-	+	+	+
d^c	+	+	-	+	+
ν	+	+	+	+	-
e	+	+	+	-	+
e^c	-	-	-	+	+
N	-	-	-	-	-

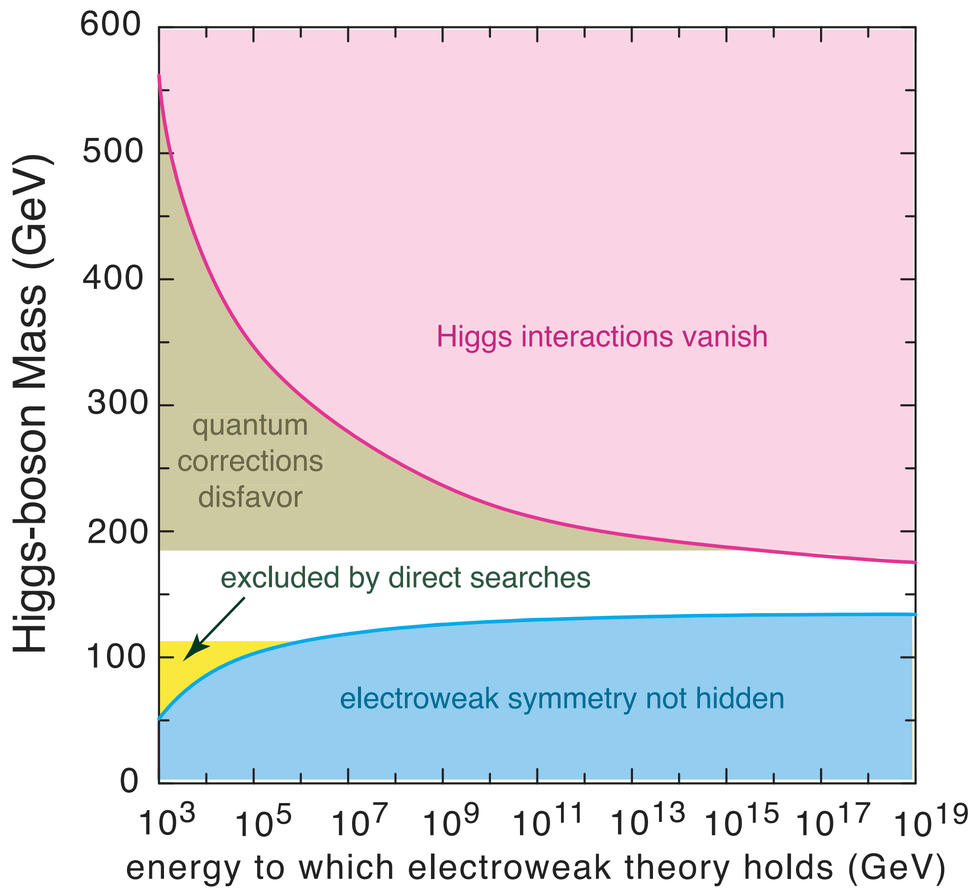
Hypercharge Y = -1/6 (R+W+B) + 1/4 (G+P)

SO(10)

N.B.: One hand rules them all!

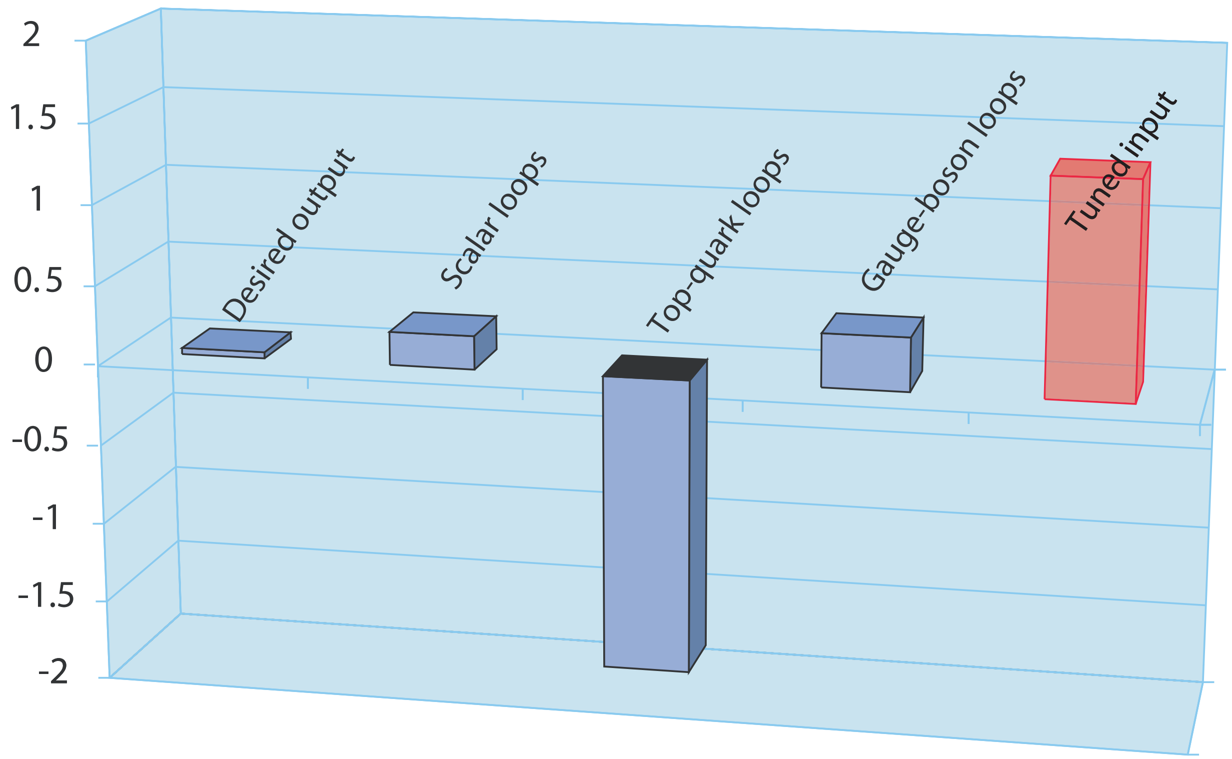


Left: quarks and leptons of one generation united in single **16**-plet of $SO(10)$ (cf. Wilczek); *Right*: geometric picture of F-theory GUTs (cf. Vafa); matter and Higgs fields confined to 6D submanifolds; intersect at 4D 'points' with enhanced E_8 symmetry where Yukawa couplings are generated. (BUT: string theory has not yet reached status of falsifiable theory.)



Consequence of perturbative extrapolation to GUT/Planck scale (with or without supersymmetry): prediction of light Higgs boson! (cf. Quigg '07)

“Secret” Supersymmetry?



Various quadratically divergent contributions to Higgs mass ($\Lambda_{\rm UV} = 5$ TeV)

Quigg’07: “... a careful balancing act is required to maintain a small Higgs-boson mass in the face of quantum corrections ... we are left to ask what enforces the balance or how we might be misreading the data.”

Veltman '81 [The Infrared-Ultraviolet Connection, Acta Physica Polonica]: "It is concluded that there is either a threshold in the TeV region, or alternatively a certain mass formula holds. This formula, when true, might be indicative for an underlying supersymmetry."

Mass relation between fermions and bosons, corresponding to cancellation of quadratic divergencies (no "tuned input"):

$$\sum_f \frac{m_f^2}{m_W^2} = \frac{3}{2} + \frac{3}{4\cos^2\theta_W} + \frac{3}{4}\frac{m_H^2}{m_W^2} \;;$$

prediction: $m_t = 69$ GeV if $m_H \ll m_W$, or $m_t = 77$ GeV if $m_H = m_W$ (large top-mass prediction before discovery of W-bosons!).

Modified mass relation with additional bosons and fermions? Specific model with 'underlying supersymmetry'? Other explanation for cancellation of quadratic divergencies (conformal symmetry ...)? New threshold in the TeV region? LHC should give us the answer!

II. The Cosmology Connection

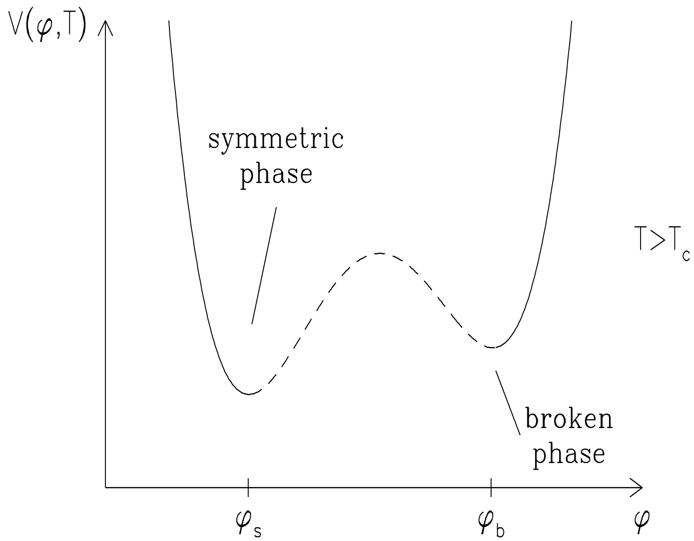
During the past decade an impressive quantitative connection between particle physics and the early universe has been established; important in two ways: unravelling early history of universe, and constraints on possible extensions of Standard Model.

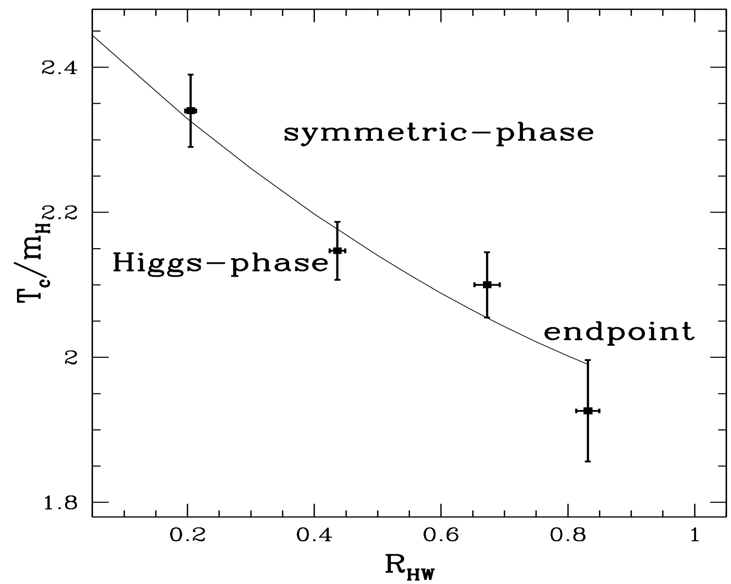
Three examples:

- Electroweak phase transition and baryogenesis
- Dark matter candidates
- Inflation and Higgs sector
- [Possible explanations of dark energy in quantum field theory, gravity and string theory]

Electroweak phase transition and baryogenesis

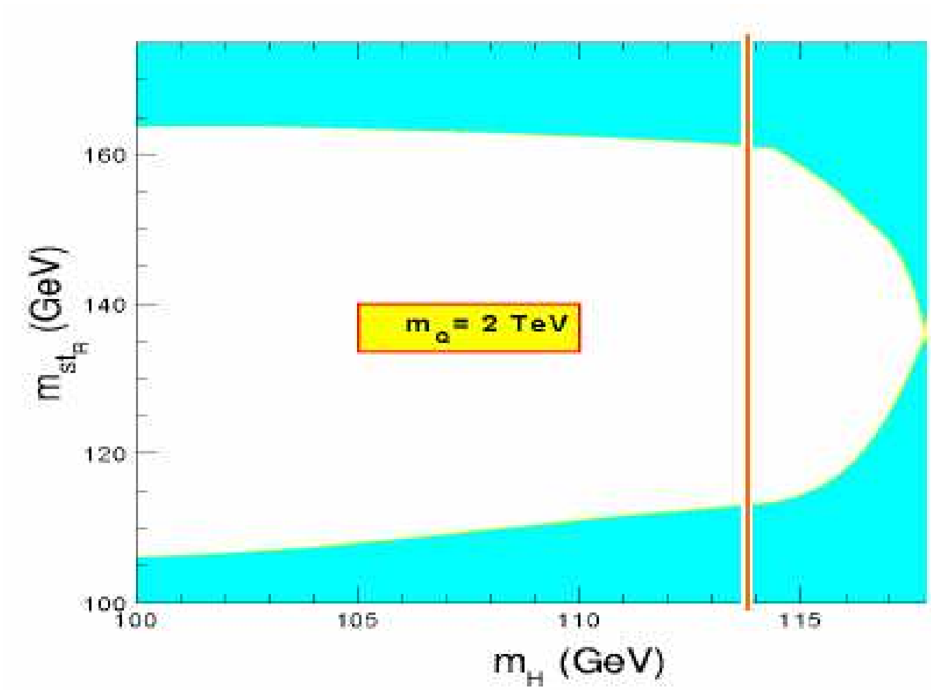
First-order phase transitions with critical end point (Csikor, Fodor, Heitger '99):





$R_{HW} = \frac{m_H}{m_W}$, critical Higgs mass: $m_H^c = 72.1 \pm 1.4$ GeV; for larger Higgs masses crossover; in Standard Model electroweak baryogenesis excluded since strongly first-order phase transition required.

Some extensions still viable: 2 Higgs doublet models, MSSM,..., but strong constraints on parameters, all testable at LHC!!



in MSSM 'exceptional' SUSY mass spectrum required: $m_{\rm stop} < m_{\rm top}$,..., other squarks very heavy (Carena, Quiros, Wagner '07); current CDF bound (note 7/09): $m_{\rm stop} > 180$ GeV; soon stringent bounds from ATLAS and CMS.

Dark Matter Candidates

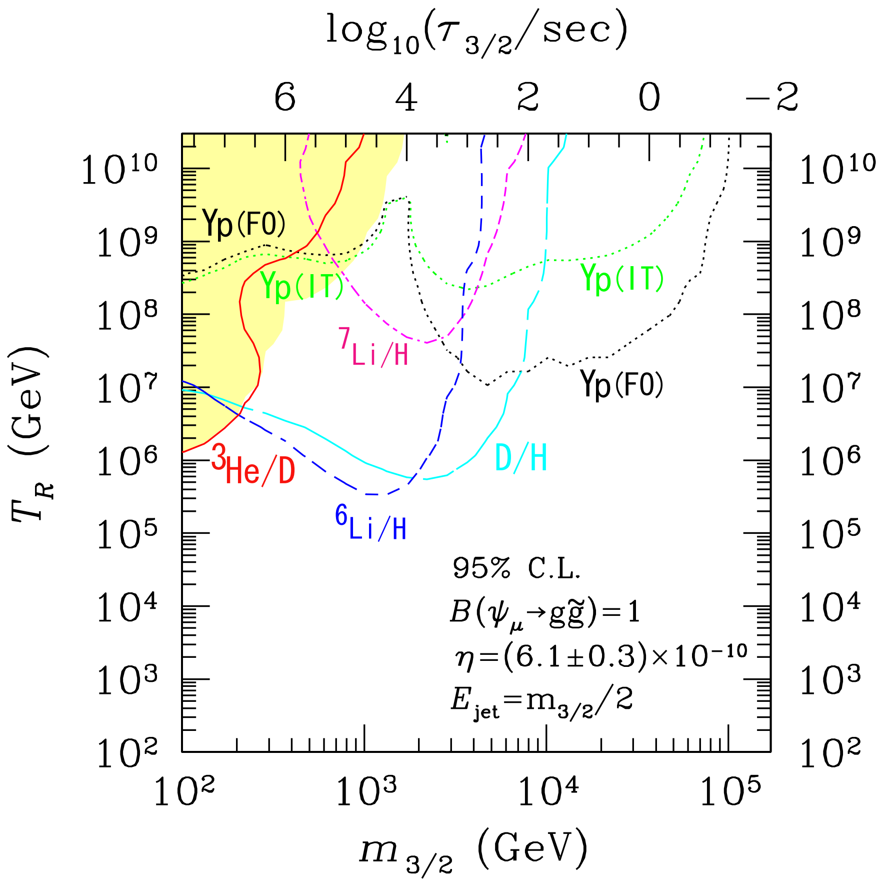
Extensions of Standard Model naturally provide candidates for dark matter; there are strong connections between cosmology (production in early universe), astroparticle physics (direct and indirect search experiments) and particle physics (signatures in collider experiments?)

Candidates include:

- Axions: well motivated by strong CP problem of QCD; searches: dark matter (Livermoore), solar radiation (CAST), light-shining-through-walls (ALPS,...); caustics in Milky Way halo (Sikivie et al. '07)?

- WIMPs: most popular DM candidate, thermal freeze-out, clear LHC signatures, consistent with electroweak baryogenesis, inconsistent with thermal leptogenesis

- Gravitinos: lightest superparticle in some patterns of supersymmetry breaking, well motivated by leptogenesis, ..., see further discussion



Leptogenesis requires high reheating temperature,

$$T_R \gtrsim 10^9 \text{ GeV} ;$$

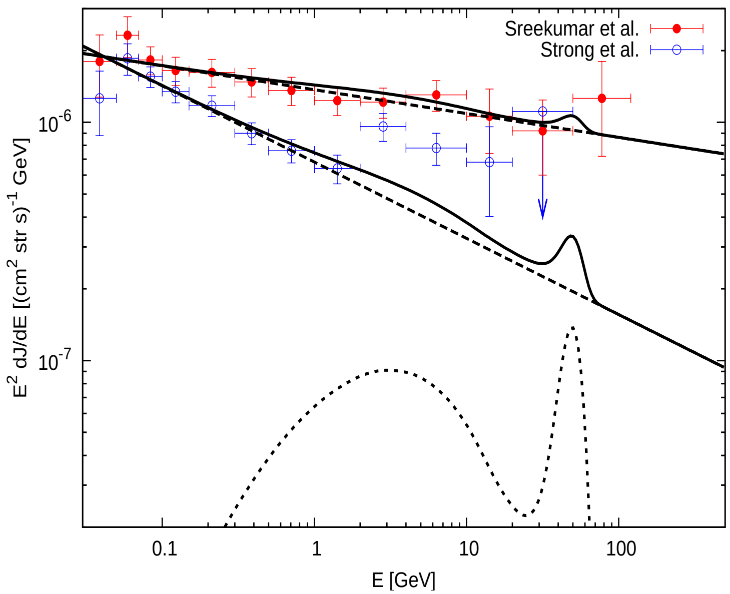
stringent upper bounds on T_R from heavy gravitino decays (Kawasaki, Kohri, Moroi '05):

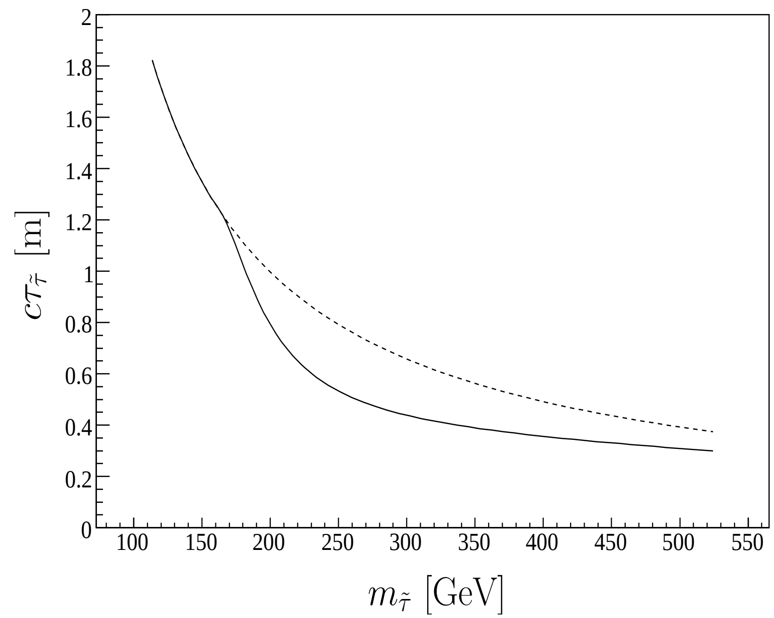
$$T_R < \mathcal{O}(1) \times 10^5 \text{ GeV} ;$$

→ standard mSUGRA with neutralino LSP incompatible with thermal leptogenesis.

Possible way out: Gravitino LSP & DM, various options for NLSP ...

Signatures of decaying dark matter at the LHC





Left: Decaying dark matter leads to photon line in diffuse gamma-ray flux (Ibarra et al. '09); current Fermi-LAT bound on lifetime: $\tau_{\rm DM} \gtrsim 10^{28}$ s; *right*: predicted decay length of $\tilde{\tau}$-NLSP as function of $\tilde{\tau}$-mass (Bobrovskyi et al. '10).

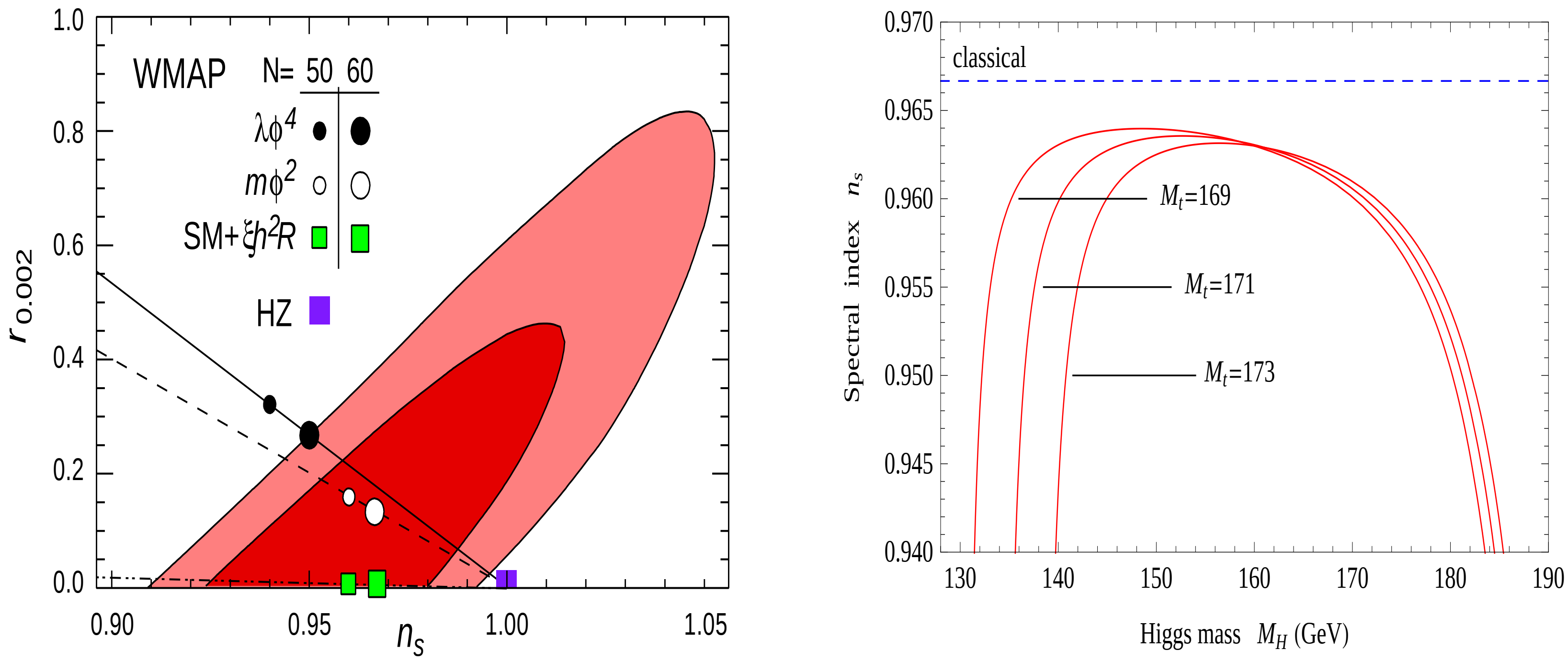
Inflation and Higgs sector

'Canonical' models of inflation: inflaton is singlet field related to moduli in string theory, supersymmetry breaking, ..., it has no gauge interactions; recent observation: the inflaton can have gauge interactions and may even be the Higgs field (Bezrukov, Shaposhnikov '07, ...)

Basic idea: "non-minimal" coupling of Higgs field to gravity:

$$\mathcal{L} = \frac{M_{\mathrm{P}}^2}{2} R - \xi H^\dagger H R + \mathcal{L}_{\mathrm{SM}} \ .$$

For $\langle H^\dagger H \rangle = \mathcal{O}(M_{\mathrm{P}}^2)$, typical during inflationary phase, significant modification of effective Planck mass! Successful prediction of CMB temperature anisotropies requires "very large" ξ. Part of Shaposhnikov's programme to describe "everything" (baryogenesis, dark matter, inflation, dark energy) in terms of Standard Model with three right-handed neutrinos.



Predictions (*left*): 'good' scalar spectral index, negligable gravitational waves (Bezrukov, Shaposhnikov '07); constraints (*right*): spectral index depends on Higgs and top masses (Barvinsky et al. '09), quantitative connection between inflation, Higgs mass and shape of Higgs potential!

SUMMARY

- Connection between particle physics and cosmology will become increasingly important: electroweak symmetry breaking, dark matter, inflation, ...

- The infrared-ultaviolet connection
  - (A) $\Lambda_{\mathrm{UV}} = v_{\mathrm{EW}}$: new strong interactions, compositeness (Higgs, quark-lepton, W-boson), string excitations, ... at TeV scale; crucial tests very soon!
  - (B) $\Lambda_{\mathrm{UV}} = \Lambda_{\mathrm{GUT}}, M_{\mathrm{P}}$: elementary Higgs boson, low-energy supersymmetry, perturbative unification,...; determination of effective Lagrangian at TeV scale in coming years, which allows reliable extrapolation.