Anders Basbøll (U of Sussex): νMSSM+3scalars+U(1)' A model for inflation, ν-mass and μ-problem solution.

- In co-operation with Tim Jones (Liverpool) and Mark Hindmarsh (Sussex)
- Work in progress
- extension to model

- Hodgson, Jack, Jones, Ross: NPB 728 (2005)

The model

- Superpotential

$$W = y_U^{ij} Q_i H_2 U_j + y_D^{ij} Q_i H_1 D_j + y_E^{ij} L_i H_1 E_j + y_N^{ij} L_i H_2 N_j + \lambda_{NN\phi}^{ij} N_i N_j \phi + \lambda_{\phi\bar{\phi}S} \phi\bar{\phi} S + \lambda_{H_2 H_1 S} H_2 H_1 S + M^2 S$$

- No additional soft terms.
- Tree potential (F-, D-terms) $V = \sum_i |F_i|^2 + \sum_A \frac{g_A^2}{2} D^A D^A$

$F_i = \frac{\partial W}{\partial \varphi}$ $\quad D^A = \sum_i \varphi_i^\dagger T^A \varphi_i$

- Extra U(1) gauge coupling: $D_E = g_E/2(-\xi + \Sigma_i q_i' |\varphi_i|^2)$
- Fayet-Iliopoulos term
- Possible charges (W allowed, anomaly free): 11-8-1=2 dimensions. Hypercharge is one.

(in example later: direction orthogonal to Y chosen)

- $\phi\bar{\phi}$ gets equal, opposite charges.

Motivation: from SM to this.

$$W = y_U^{ij} Q_i H_2 U_j + y_D^{ij} Q_i H_1 D_j + y_E^{ij} L_i H_1 E_j + y_N^{ij} L_i H_2 N_j + \lambda_{NN\phi}^{ij} N_i N_j \phi + \lambda_{\phi\bar{\phi}S} \phi\bar{\phi} S + \lambda_{H_2 H_1 S} H_2 H_1 S + M^2 S$$

- SUSY (High energy divergencies, Dark matter)
- Anomaly mediated SUSY breaking (D or F term):
  - no soft terms - no nonrenormalisable terms.
  Thus: highly predictive - but tachyonic sleptons.
- Righthanded neutrinos (and y_N): massive neutrinos.
- Singlet S: Inflaton. Linear, not higher order terms:

Flat Potential (ignoring other fields) $V = |F_S|^2 = |\frac{\partial W}{\partial S}|^2 = M^4$

(when $M, \sqrt{\xi} << \langle s \rangle$)

Extra U(1)': FI- term possible, thus VEV to ϕ today and thus neutrino mass - and no tachyonic sleptons?

$\bar{\phi}$ to avoid anomalies. $\phi\bar{\phi}$ SM singlets.

Potential - find minimum

$$W = y_U^{ij} Q_i H_2 U_j + y_D^{ij} Q_i H_1 D_j + y_E^{ij} L_i H_1 E_j + y_N^{ij} L_i H_2 N_j + \lambda_{NN\phi}^{ij} N_i N_j \phi + \lambda_{\phi\overline{\phi}S} \phi\overline{\phi} S + \lambda_{H_2 H_1 S} H_2 H_1 S + M^2 S$$

- During inflation: $M, \sqrt{\xi} << \langle s \rangle$
- Vmin=M^4 (from F_s - cannot be balanced by VEV in Higgs or Φ sectors.)
- To avoid F-terms $\langle H_{1,2}^{\alpha} \rangle = \langle \phi \rangle = \langle \overline{\phi} \rangle = \langle N_i \rangle = 0$
- D-terms zero: 32 complex dimensions: 45-13 (each gauge generator gives real non-flat direction, 1 real gauge choice.)
- F-terms: only from Higgses can be nonzero.
  - Flat space 28=32-4 complex dim's.
- Simplicity: MSSM yukawas: diagonal.

More on D-flatness

- For SU(3) X SU(2) X U(1) much studied.
- Catalogue of monomials (28 types) and lifting:
- Gherghetta, Kolda, Martin, NPB 468, 37 (1996)
- AB, IJMPA A25 (2010) (gen. structure, 712 mon's)

Flat space is not additive (but is scalar multiplicative - all terms 4th order in fields).

- U(1)' removes this: some fields get VEVs to balance ξ - but without contributing to other D's.
- “All fields vanishes” not part of flat space!
- MSSM: Loop corrections vanish.
- Here: No hope of complete analytic investigation.
- Test case (next slide).

Is minimum unique?

- $V_{loop} = \sum_i (-)^F M_i^4 Log\left(\frac{M_i^2}{\mu^2}\right)$
- MSSM : no scales - except μ (from Higgs)

- but soft terms.

- Here: <s>, M, ξ
- Get a handle: $L_1L_2E_3$, $DDDL_1L_2$ only.
- VEVs (0<=f<=sqrt[3])
- LLE (f=sqrt[3])
- DDDLL (f=0)
  - gives $V=M^4$ at tree level.

$$\tilde{\tau}^c = f\sqrt{\frac{\xi}{15}}$$
$$\tilde{\nu}_e = \tilde{\mu} = \sqrt{1+\frac{2}{3}f^2}\sqrt{\frac{\xi}{15}}$$
$$\tilde{d}^1 = \tilde{s}^2 = \tilde{b}^3\sqrt{1-\frac{1}{3}f^2}\sqrt{\frac{\xi}{15}}$$

Gauge choice: All VEVs are real.

VEVs and masses

- 52 gauge mass^2 are identical for fermions and bosons (since D=0, SUSY not broken) $g_2^2(1+\frac{2}{3}f^2)\left(\frac{\xi}{15}\right)$
- for each generator (something like)

(1 real scalar, 3 real vector polar. 2 complex spinor)

$\phi\bar{\phi}$ sector: fermions $|\lambda_{\phi\bar{\phi}S}|^2\langle s\rangle^2$ (4 times)

bosons $|\lambda_{\phi\bar{\phi}S}|^2\langle s\rangle^2 \pm |\lambda_{\phi\bar{\phi}S}|M^2$ (2 times each)

Once <s> falls below its critical value: $s_c = M/\sqrt{|\lambda_{\phi\bar{\phi}S}|}$

some bosonic mass^2 <0

- cosmic string production.

- Constraints on D,F-term inflation:

Battye, Garbrecht, Moss , arXiv:1001.0769

$H_1, H_2, Q_3, L_3, E_1, E_2, N_1, N_2$ sector

- Bosons: solutions to 4.th order equation (twice each)

$$x^4 - 2(V+A+N)x^3 + [(V+A+N)^2 + 2NV - B^2]x^2$$
$$-[2NV(V+A+N) - B^2(V+A)]x + NV[NV - B^2]$$

$$A = |\lambda_{H_2H_1S}|^2\langle s\rangle^2 \;\; B = |\lambda_{H_2H_1S}|M^2 \;\; N = |y_N^{11}|^2\left(1+\frac{2}{3}f^2\right)\frac{\xi}{15}$$

$$V = \left((|y_D^{11}|^2 + |y_D^{22}|^2 + |y_D^{33}|^2)\left(1-\frac{1}{3}f^2\right) + |y_E^{22}|^2\left(1+\frac{2}{3}f^2\right) + |y_E^{33}|^2 f^2\right)\frac{\xi}{15}$$

- Descartes: Iff alternating signs of coef's, all roots>0.

$$\left((|y_D^{11}|^2 + |y_D^{22}|^2 + |y_D^{33}|^2)\left(1-\frac{1}{3}f^2\right) + |y_E^{22}|^2\left(1+\frac{2}{3}f^2\right) + |y_E^{33}|^2 f^2\right)|y_N^{11}|^2\left(1+\frac{2}{3}f^2\right)\frac{\xi}{15} \geq |\lambda_{H_2H_1S}|^2 M^4$$

Also solutions to same system under E_1N_2<->N_1E_2

- If M=0, reduces to fermion masses.
- WARNING: See what happens if y_N^{11} set to zero.

Mass conclusion

- Masses depend on which FD (f dependence)

- huge degeneracy of MSSM FD broken.

- The minimum of the LLE, DDDLL case: upper limit to potential (but not on inflation parameters).

- When parameters found to match data: check other FD's for a different minimum - see next slide.

- FIRST result: For the 3 new scalars alone (omitting the ξ-part and thus MSSM VEVs):
- Scalar perturbations match WMAP when $\lambda_{\phi\bar{\phi}S}$ ~0.1, M~$10^{-3}m_{PL}$ N~60.

A larger test space - 4 dims

- All vevs sqrt[ξ/5] times the following factors:
- u_2, c_3, t_1 : A (Q: color=generation+1)
- d_2, s_3, b_1: B (Q: color=generation+2)
- u_1^c, c_2^c, t_3^c: R (U: color=generation)
- d_1^c, s_2^c, b_3^c: G (D: color=generation)
- ν_e: sqrt[$1+2A^2-B^2-2G^2+R^2$]
- μ: sqrt[$1-A^2+2B^2-2G^2+R^2$]
- τ^c: sqrt[$1-3G^2+3R^2$]

- LLE: A=B=G=R=0
- DDDLL: A=B=R=0, G=1/sqrt[3]
- QQQL,UUUEE wrong U(1)' charge (ξ>0).

Implications

- During inflation: we calculate V(<s>).
- This postdicts inflation parameters.
- High predictivity: Only M breaks SUSY. Very few new couplings. $\lambda_{\phi\overline{\phi}S}$ really new.
- ($\lambda^{ij}_{NN\phi}$, $\lambda_{H_2H_1S}$ replace others.)
- <s> will decrease as V(<s>) dictates.
- Inflation ends quickly when <s> drops to s_c.
- Cosmic strings (with strong bounds) are produced.
- V=0 possible.
- Either or both pairs get VEV
- Want: Φ: to give ν masses (<H> negligible).
- to balance ξ so MSSM fields all VEV-less.

$$F_S = M^2 + \lambda_{\phi\overline{\phi}S}\phi\overline{\phi} + \lambda_{H_2H_1S}H_2H_1$$

$$(\phi, \overline{\phi}), (H_1, H_2)$$

Constraints, summary.

- WMAP scalar perturbations.
- Neutrino mass differences.
- SM results.

- Limits on tensor perturbations, slow-roll parameters, spectral tilt from inflation.
- Limits on absolute neutrino mass.

- Prediction: Sparticle spectrum @ LHC and elsewhere (including Dark Matter).

Conclusions

- The presented model has few new parameters compared to SM.
- It is highly predictive - could be falsified by LHC.

- Still work to be done.

REUTERS July 1st 2008:
"Merkel says very concerned about inflation"