Introduction to MSSM

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Talk Outline

- Supersymmetry (SUSY) Basics
    - Superfield formalism
    - Constructing SUSY invariant theory
    - SUSY breaking
- Minimal Supersymmetric Standard Model (MSSM)
    - SUSY preserving Lagrangian and soft-breaking terms
        - R-parity
    - Superpartner Mixing
- Implications
    - Dark Matter
    - 125 GeV Higgs

Supersymmetry (SUSY)

Reviews: [Wess & Bagger]

Symmetry: Fermions ⇔ Bosons

$Q\ |\Phi\rangle = |\Psi\rangle \quad ; \quad Q\ |\Psi\rangle = |\Phi\rangle$

Q_α is a spinorial charge

SUSY algebra:

$$\left\{Q_\alpha\,,\,\bar{Q}_{\dot\beta}\right\} = 2\sigma^\mu_{\alpha\dot\beta}P_\mu$$

$$\left\{Q_\alpha\,,\,Q_\beta\right\} = \left\{\bar{Q}_{\dot\alpha}\,,\,\bar{Q}_{\dot\beta}\right\} = 0$$

$$[P^\mu\,,\,Q_\alpha] = [P^\mu\,,\,\bar{Q}_{\dot\alpha}] = 0$$

Superfield

SUSY algebra realized through a Superfield $\Phi\left(x_\mu, \theta, \bar{\theta}\right)$

θ are fermionic (Grassmann) coordinates that anticommute: θ_α , $\alpha = \{1,2\}$

$\{\theta,\theta\} = \{\theta,\bar{\theta}\} = \{\bar{\theta},\bar{\theta}\} = 0 \implies (\theta_1)^2 = (\theta_2)^2 = 0$

Define $\theta\theta \equiv \theta^\alpha\theta_\alpha$; $\bar{\theta}\bar{\theta} \equiv \bar{\theta}_{\dot{\alpha}}\bar{\theta}^{\dot{\alpha}}$; $\theta^\alpha \equiv \epsilon^{\alpha\beta}\theta_\beta$; $\bar{\theta}_{\dot{\alpha}} \equiv \epsilon_{\dot{\alpha}\dot{\beta}}\theta^{\dot{\beta}}$; $\epsilon^{12} = \epsilon_{21} = +1$

- Chiral Superfield
  - $\bar{D}\Phi_L = 0$; $D\Phi_R = 0$
  - $\Phi_L = \phi(y) + \sqrt{2}\theta\psi_L(y) + \theta\theta F(y)$

    F : auxiliary field

$$\delta_\xi \phi = \sqrt{2}\xi\psi$$
$$\delta_\xi \psi = i\sqrt{2}\sigma^m\bar{\xi}\partial_m\phi + \sqrt{2}\xi F$$
$$\delta_\xi F = i\sqrt{2}\bar{\xi}\bar{\sigma}^m\partial_m\psi$$

- Vector Superfield
  - $V = V^\dagger$
  - $V(x,\theta,\bar{\theta}) = -\theta\sigma_\mu\bar{\theta}A^\mu(x) + i\theta\theta\bar{\theta}\bar{\lambda}(x) - \bar{\theta}\bar{\theta}\theta\lambda(x) + \frac{1}{2}\theta\theta\bar{\theta}\bar{\theta}D(x)$

    D : auxiliary field

$$\delta_\xi A_{mn} = i\left[\left(\xi\sigma^n\partial_m\bar{\lambda} + \bar{\xi}\bar{\sigma}^n\partial_m\lambda\right) - (n \leftrightarrow m)\right]$$
$$\delta_\xi \lambda = i\xi D + \sigma^{mn}\xi A_{mn}$$
$$\delta_\xi D = \bar{\xi}\bar{\sigma}^m\partial_m\lambda - \xi\sigma^m\partial_m\bar{\lambda}$$

Constructing a SUSY theory

Under a SUSY transformation, F and D transform into total derivatives

- So they can be used for constructing SUSY invariant $\mathcal{L}$

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A SUSY gauge invariant theory

$$\mathcal{L} = \Phi_i^\dagger e^{2gV}\Phi_i\Big|_{\theta\theta\bar{\theta}\bar{\theta}} + \left(\mathcal{W}(\Phi_i)|_{\theta\theta} + h.c.\right) + \frac{1}{32g^2}\, W_\alpha W^\alpha|_{\theta\theta}$$

Superpotential $\mathcal{W}(\Phi)$, a Holomorphic function

Gauge Kinetic Function $W_\alpha = -\frac{1}{4}\bar{D}\bar{D}e^{-V}D_\alpha e^V$

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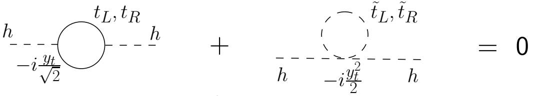
Eliminating the Auxiliary fields

$$\begin{aligned}\mathcal{L} =& |D_\mu \phi_i|^2 - i\bar{\psi}_i \sigma_\mu D^\mu \psi_i - g\sqrt{2}\left(\phi_i^* T^a \psi_i \lambda^a + \lambda^{a\dagger} \psi^\dagger T^a \phi_i\right) \\ & - \left(\frac{1}{2}\frac{\partial^2 \mathcal{W}(\phi_i)}{\partial\phi_j \partial\phi_k}\psi_j\psi_k + h.c.\right) - \left|\frac{\partial \mathcal{W}(\phi_i)}{\partial \phi_j}\right|^2 \\ & - \frac{1}{4}F^a_{\mu\nu}F_a^{\mu\nu} - \frac{1}{2}\sum_a \left|g\phi_i^* T^a_{ij}\phi_j\right|^2 - i\lambda^{a\dagger}\bar{\sigma}_\mu D^\mu \lambda_a\end{aligned}$$

Consequences

Solution to gauge hierarchy problem



Λ^2 divergence cancelled

[Romesh Kaul's talk]

(Similarly $W^{\pm}$, Z divergences cancelled by $\tilde{\lambda}$)

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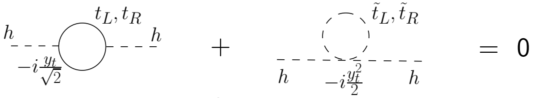

Λ^2 divergence cancelled [Romesh Kaul's talk]

(Similarly $W^{\pm}$, Z divergences cancelled by $\tilde{\lambda}$)

- Lightest SUSY Particle (LSP) stable dark matter (if R_p conserved)
- Gauge Coupling Unification - SUSY $SO(10)$ GUT
  Includes $\nu_R \Rightarrow$ Neutrino mass via seesaw

SUSY breaking

- Exact SUSY $\implies M_\psi = M_\phi \quad ; \quad M_A = M_{\tilde{\lambda}}$
  - So experiment $\implies$ SUSY must be broken
- SUSY broken if and only if $\langle 0|H|0\rangle > 0$
  - Spontaneous SUSY breaking
    - O'Raifeartaigh F-term breaking
    - Fayet-Iliopoulos D-term breaking
  - $STr(M^2) = 0 \quad \implies$ cannot break SUSY spontaneously using SM superfield
    - Hidden sector breaking $\underset{Mediation}{\longleftrightarrow}$ Communicated to SM

    Spectrum depends on Mediation type + RGE
- In effective low-energy theory
  - Explicit soft-breaking terms, i.e., with dimensionful parameters

MSSM

The Minimal Supersymmetric Standard Model (MSSM)

Reviews: [Martin] [Drees] [Drees,Godbole,Roy] [Baer,Tata]

MSSM fields

To every SM particle, add a ***superpartner*** *(with spin differing by* 1/2*)*

Matter fields (Chiral Superfields)

	$(SU(3), SU(2))_{U(1)}$	Components
Q	$(3, 2)_{1/6}$	$(\tilde{q}_L, q_L, F_Q)$; $\tilde{q}_L = \begin{pmatrix} \tilde{u}_L \\ \tilde{d}_L \end{pmatrix}$; $q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$
U^c	$(\bar{3}, 1)_{-2/3}$	$(\tilde{u}^*_R, u^c_R, F_U)$
D^c	$(\bar{3}, 1)_{1/3}$	$(\tilde{d}^*_R, d^c_R, F_D)$
L	$(1, 2)_{-1/2}$	$(\tilde{\ell}_L, \ell_L, F_L)$; $\tilde{\ell}_L = \begin{pmatrix} \tilde{\nu}_L \\ \tilde{e}_L \end{pmatrix}$; $\ell_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$
E^c	$(1, 1)_1$	$(\tilde{e}^*_R, e^c_R, F_E)$
(N^c)	$(1, 1)_0$	$(\tilde{\nu}^*_R, \nu^c_R, F_N)$

Gauge fields (Vector Superfields)

	Components
$SU(3)$	$(g_\mu, \tilde{g}, D_3)$
$SU(2)$	$(W_\mu, \tilde{W}, D_2)$
$U(1)$	$(B_\mu, \tilde{B}, D_1)$

Higgs fields (Chiral Superfields)

	$(SU(3), SU(2))_{U(1)}$	Components
H_u	$(1, 2)_{1/2}$	$(h_u, \tilde{h}_u, F_{H_u})$; $h_u = \begin{pmatrix} h_u^+ \\ h_u^0 \end{pmatrix}$; $\tilde{h}_u = \begin{pmatrix} \tilde{h}_u^+ \\ \tilde{h}_u^0 \end{pmatrix}$
H_d	$(1, 2)_{-1/2}$	$(h_d, \tilde{h}_d, F_{H_d})$; $h_d = \begin{pmatrix} h_d^0 \\ h_d^- \end{pmatrix}$; $\tilde{h}_d = \begin{pmatrix} \tilde{h}_d^0 \\ \tilde{h}_d^- \end{pmatrix}$

MSSM Superpotential

Write most general $\mathcal{W}$ consistent with $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$

- $\mathcal{W} = U^c y_u Q H_u - D^c y_d Q H_d - E^c y_e L H_d + \mu H_u H_d + (N^c y_n L H_u)$
- $\mathcal{W}_{\Delta L} = L H_u + L E^c L + Q D^c L \; ; \qquad \mathcal{W}_{\Delta B} = U^c D^c D^c$
    - $\mathcal{W}_{\Delta L} + \mathcal{W}_{\Delta B}$ induce proton decay : $\quad \tau_p \sim 10^{-10} s$ for $\tilde{m} \sim 1$ TeV

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So impose Matter Parity $R_M = (-1)^{3(B-L)}$ to forbid ΔL *and* ΔB terms

For components $\implies$ R-parity $R_p = (-1)^{3(B-L)+2s}$

$R_p(particle) = +1 \quad , \quad R_p(sparticle) = -1$

Consequence : The Lightest SUSY Particle (LSP) is stable

- Cosmologically stable Dark Matter
- Missing Energy at Colliders

Soft SUSY breaking

Effective parametrization with explicit soft-SUSY-breaking terms

$$\mathcal{L}^{soft}_{SUSY\ Br} \supset -\tilde{Q}^\dagger \tilde{m}^2_Q \tilde{Q} - \tilde{u}^\dagger_R \tilde{m}^2_u \tilde{u}_R - \tilde{d}^\dagger_R \tilde{m}^2_d \tilde{d}_R - \tilde{L}^\dagger \tilde{m}^2_L \tilde{L} - \tilde{e}^\dagger_R \tilde{m}^2_e \tilde{e}_R - (\tilde{\nu}^\dagger_R \tilde{m}^2_\nu \tilde{\nu}_R)$$
$$-\frac{1}{2} M_1 \tilde{B}\tilde{B} - \frac{1}{2} M_2 \tilde{W}\tilde{W} - \frac{1}{2} M_3 \tilde{g}\tilde{g} + h.c.$$
$$-\tilde{u^c} A_u \tilde{Q} H_u + \tilde{d^c} A_d \tilde{Q} H_d + \tilde{e^c} A_e \tilde{L} H_d - (\tilde{\nu^c} A_\nu \tilde{L} H_u) + h.c.$$
$$-m^2_{H_u} H^\dagger_u H_u - m^2_{H_d} H^\dagger_d H_d - (B\mu H_u H_d + h.c.)$$

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$$-\tilde{u^c} A_u \tilde{Q} H_u + \tilde{d^c} A_d \tilde{Q} H_d + \tilde{e^c} A_e \tilde{L} H_d - (\tilde{\nu^c} A_\nu \tilde{L} H_u) + h.c.$$
$$-m^2_{H_u} H^\dagger_u H_u - m^2_{H_d} H^\dagger_d H_d - (B\mu H_u H_d + h.c.)$$

UV SUSY breaking and mediation dynamics will set these parameters

- Eg: Gravity Mediation (MSUGRA, CMSSM)
  - Inputs $\tilde{m}_0$,$M_{1/2}$, A_0, tan β, sign(μ) at GUT scale
  - TeV scale values determined by RGE

Electroweak symmetry breaking (EWSB)

$$\langle H_u \rangle = \frac{1}{\sqrt{2}} \left(\begin{array}{c} 0 \\ v_u \end{array} \right) ; \quad \langle H_d \rangle = \frac{1}{\sqrt{2}} \left(\begin{array}{c} v_d \\ 0 \end{array} \right); \quad v^2 = v_u^2 + v_d^2; \qquad \tan\beta \equiv \frac{v_u}{v_d};$$

Physical Higgses: h^0, H^0, A^0, $H^\pm$

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Physical Higgses: h^0, H^0, A^0, $H^\pm$

$$\mathcal{V} = (|\mu|^2 + m_{H_u}^2)|h_u|^2 + (|\mu|^2 + m_{H_d}^2)|h_d|^2 - (b_\mu h_u h_d + h.c.) + \frac{1}{8}(g^2 + g'^2)(|h_u|^2 - |h_d|^2)^2$$

Minimization and EWSB

$$\sin(2\beta) = \frac{2b_\mu}{m_{H_u}^2 + m_{H_d}^2 + 2|\mu|^2} \qquad \text{and} \qquad m_Z^2 = \frac{|m_{H_d}^2 - m_{H_d}^2|}{\sqrt{1 - \sin^2(2\beta)}} - m_{H_u}^2 - m_{H_d}^2 - 2|\mu|^2$$

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- So we need μ^2 (SUSY preserving param) $\sim m^2$ (SUSY br param)! Why?
  - This is called the μ-problem

125 GeV Higgs

At 1-loop [Haber, Hempfling, Hoang ,1997] [Debtosh's thesis]

$$m_h^2 \approx m_Z^2 \cos^2(2\beta) + \frac{3g_2^2 m_t^4}{8\pi^2 m_W^2}\left[\ln\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right) + \frac{X_t^2}{m_{\tilde{t}_1} m_{\tilde{t}_2}}\left(1 - \frac{X_t^2}{12 m_{\tilde{t}_1} m_{\tilde{t}_2}}\right)\right]$$

where $X_t = A_t - \mu \cot\beta$

- $m_h = 125$ GeV needs sizable loop contribution
  - Hard! Needs large $m_{\tilde{t}_1} m_{\tilde{t}_2}$ or large X_t^2
  - But $\delta m_{H_u}^2 \approx \frac{3g_2^2 m_t^4}{8\pi^2 m_W^2}\left[\ln\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right) + \frac{X_t^2}{2 m_{\tilde{t}_1} m_{\tilde{t}_2}}\left(1 - \frac{X_t^2}{6 m_{\tilde{t}_1} m_{\tilde{t}_2}}\right)\right]$

    So fine-tuning necessary to keep m_Z^2 correct (*cf* previous EWSB relation)

    "Little hierarchy problem"

Neutralino mixing

Neutralino: Neutral EW gauginos $(\tilde{B}, \tilde{W}^3, \tilde{H}_u^0, \tilde{H}_d^0)$: Majorana states

$\mathcal{L} \supset$

$$-\frac{1}{2} \begin{pmatrix} \tilde{B} & \tilde{W}^3 & \tilde{H}_u^0 & \tilde{H}_d^0 \end{pmatrix} \begin{pmatrix} M_1 & 0 & -c_\beta s_W m_Z & s_\beta s_W m_Z \\ 0 & M_2 & c_\beta c_W m_Z & -s_\beta c_W m_Z \\ -c_\beta s_W m_Z & c_\beta c_W m_Z & 0 & -\mu \\ s_\beta s_W m_Z & -s_\beta c_W m_Z & -\mu & 0 \end{pmatrix} \begin{pmatrix} \tilde{B} \\ \tilde{W}^3 \\ \tilde{H}_u^0 \\ \tilde{H}_d^0 \end{pmatrix}$$

Diagonalizing this $\begin{pmatrix} \tilde{B} \\ \tilde{W}^3 \\ \tilde{H}_u^0 \\ \tilde{H}_d^0 \end{pmatrix} \to \begin{pmatrix} \tilde{\chi}_1^0 \\ \tilde{\chi}_2^0 \\ \tilde{\chi}_3^0 \\ \tilde{\chi}_4^0 \end{pmatrix}$: the mass eigenstates

Chargino mixing

Chargino: Charged EW gauginos $(\tilde{W}^{\pm}, \tilde{H}^{\pm})$, $\tilde{w}^{\pm} = \tilde{w}_1 \pm i\tilde{w}_2$

Form Dirac states $\tilde{W}^+ = \begin{pmatrix} \tilde{W}^+_\alpha \\ \tilde{W}^{-\dot{\alpha}} \end{pmatrix}$; $\tilde{H}^+ = \begin{pmatrix} \tilde{H}^+_{u\,\alpha} \\ \tilde{H}_d^{-\dot{\alpha}} \end{pmatrix}$

$$\mathcal{L} \supset -\begin{pmatrix} \overline{\tilde{W}^+} & \overline{\tilde{H}^+} \end{pmatrix} \left(M_\chi P_L + M_\chi^\dagger P_R\right) \begin{pmatrix} \tilde{W}^+ \\ \tilde{H}^+ \end{pmatrix} + h.c.$$

where $M_\chi = \begin{pmatrix} M_2 & \sqrt{2}\sin\beta\, m_W \\ \sqrt{2}\cos\beta\, m_W & \mu \end{pmatrix}$

Diagonalizing this $\begin{pmatrix} \tilde{W}^+ \\ \tilde{H}^+ \end{pmatrix} \to \begin{pmatrix} \tilde{\chi}_1^+ \\ \tilde{\chi}_2^+ \end{pmatrix}$: the mass eigenstates

Scalar mixing

Eg. stop sector $(\tilde{t}_L, \tilde{t}_R)$

$$\mathcal{L} \supset -\begin{pmatrix} \tilde{t}_L^* & \tilde{t}_R^* \end{pmatrix} \begin{pmatrix} \tilde{m}_{LL}^2 + m_t^2 + \Delta_L & (v_u A_t - \mu^* \cot\beta\, m_t)^* \\ (v_u A_t - \mu^* \cot\beta\, m_t) & \tilde{m}_{RR}^2 + m_t^2 + \Delta_R \end{pmatrix} \begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix}$$

where $\Delta = (T_3 - Q s_W^2)\, \cos(2\beta)\, m_Z^2$

Diagonalizing this $\begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix} \to \begin{pmatrix} \tilde{t}_1 \\ \tilde{t}_2 \end{pmatrix}$: the mass eigenstates

Flavor Issues

Flavor Problem

- In general $\tilde{m}_{ij}$ can have arbitrary flavor structure and phases (MSSM has 9 new phases + 1 CKM phase)
  - FCNC & EDM experiments severely constrain these
    - some deeper reason (in SUSY br mediation)?
  - Minimal Flavor Violation (MFV)
    - Only CKM phase

Dark Matter (DM)

With R_p conserved, a superpartner (odd) cannot decay to SM (even)
$\therefore$ Lightest Supersymmetric Particle (LSP) is stable

LSP is in thermal equilibrium in the early universe, and left over today as Dark Matter

- $\tilde{\chi}_1^0$ LSP with ~ 100 GeV mass is a good DM candidate
    - Weakly Interacting Massive Particle (WIMP)

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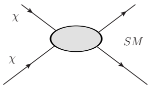
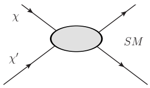
It's number density can be depleted by annihilating with another sparticle

Self-annihilation



Co-annihilation



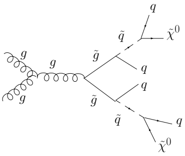
Could be detected in ongoing experiments

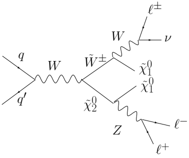
- Direct detection (on earth) $\psi N \to \psi N$
- Indirect detection (cosmic rays) $\psi\psi \to \gamma\gamma,\ e^+e^-, \ldots$

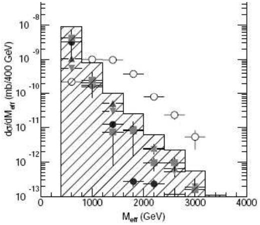
Aside: Almost pure ν_R, if LSP, could be non-thermal DM

SUSY at LHC

- Cascade decays
- R_p conservation $\Longrightarrow$ Missing energy signals







[ATLAS Physics TDR]

- Can we determine the spin and couplings to show SUSY?
  - Angular distributions

Conclusions

- Supersymmetry solves the Heirarchy Problem
- MSSM is an effective theory at the TeV scale
  - SUSY breaking in hidden sector
  - Communicated to SM via mediation mechanism
    (which determine the MSSM parameters)
    - Gravity mediation, Gauge mediation, Anomaly mediation
- R_p conservation
  - Dark Matter Candidate
  - Missing Energy at Colliders
- 14 TeV LHC run crucial for SUSY

BACKUP SLIDES

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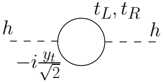
Standard Model (SM) problems

- Gauge hierarchy problem ($M_{EW} \ll M_{Pl}$)
  Electroweak scale : $M_{EW} = 10^3$ GeV   Gravity scale : $M_{Pl} = 10^{19}$ GeV
  - Higgs sector unstable   (quadratic divergence)
- Fermion mass hierarchy problem ($m_e \ll m_t$)
  - Flavor symmetry?
- What is the dark matter
- Inadequate source of CP violation for observed baryon asymmetry
- Cosmological constant problem

Gauge hierarchy problem in detail

$$\mathcal{L}_{SM} \supset -\frac{1}{2} m_h^2 h^2 + \left(-\frac{y_t}{\sqrt{2}} h \bar{t}_R t_L + h.c. \right) + \ldots$$

Higgs mass is not protected by any symmetry!



$$\frac{\delta m_h^2}{2} = -\frac{3y_t^2}{8\pi^2}\Lambda^2$$

(Λ is momentum cut-off)

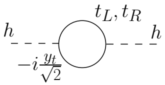
Quadratic divergence! $\Longrightarrow$ unnatural (fine-tuning)

$m_h = 125$ GeV ; $\Lambda \sim M_{pl} = 10^{19}$ GeV

Gauge hierarchy problem in detail

$$\mathcal{L}_{SM} \supset -\frac{1}{2} m_h^2 h^2 + \left(-\frac{y_t}{\sqrt{2}} h\bar{t}_R t_L + h.c.\right) + \ldots$$

Higgs mass is not protected by any symmetry!



$$\frac{\delta m_h^2}{2} = -\frac{3y_t^2}{8\pi^2}\Lambda^2$$ (Λ is momentum cut-off)

Quadratic divergence! $\Longrightarrow$ unnatural (fine-tuning)

$m_h = 125$ GeV ; $\Lambda \approx M_{pl} = 10^{19}$ GeV

New physics (BSM) restores naturalness?

Below what scale (Λ) should it appear?

Fine-tuning measure: $f_T \equiv \frac{m_h^2}{\delta m_h^2}$

$f_T > 0.1 \Longrightarrow \Lambda < 2\text{TeV}$ (for $m_h = 120$ GeV)

So expect new physics below 2 TeV scale

SM problems cured by Physics Beyond SM (BSM) ?

Some BSM proposals

- Supersymmetry
- Strong dynamics (Technicolor, Composite Higgs)
- **Extra dimensions**
  - Flat extra dims
  - Warped (AdS space) extra dim

    5-D gravity theory in AdS $\underset{DUAL}{\longleftrightarrow}$ 4-D conformal field theory (CFT)

    AdS/CFT correspondence [Maldacena 97]
- Little Higgs

LHC Data (SUSY jets + MET)