Physics Beyond the Standard Model

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January 17, 2013

Outline

- Why do we expect physics beyond the Standard Model?
- Some scenarios for BSM physics
  - Supersymmetry
  - Grand Unification
  - Neutrinos
  - Dark matter (& dark energy)
  - Extra dimensions $\leftarrow$ skipped
  - String theory $\leftarrow$ skipped
- What did we learn from the LHC so far?
- Emphasis on coherent picture and not on completeness (impossible)

The Standard Model of Particle Physics

Gauge group

$$\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$$

Particle content

Q	$(\mathbf{3},\mathbf{2})_{1/3}$	L	$(\mathbf{1},\mathbf{2})_{-1}$	H	$(\mathbf{1},\mathbf{2})_{1}$	A	$(\mathbf{1},\mathbf{1})_0$
$\bar{u}$	$(\overline{\mathbf{3}},\mathbf{1})_{-4/3}$	$\bar{e}$	$(\mathbf{1},\mathbf{1})_{2}$			W	$(\mathbf{1},\mathbf{3})_0$
$\bar{d}$	$(\overline{\mathbf{3}},\mathbf{1})_{2/3}$	$\bar{\nu}$	$(\mathbf{1},\mathbf{1})_{0}$			G	$(\mathbf{8},\mathbf{1})_0$

Lagrangian (Lorentz + gauge + renormalizable)

$$\mathcal{L} = -\frac{1}{4} G^{\alpha}_{\mu\nu} G^{\alpha\mu\nu} + \ldots \overline{Q}_k \not{D} Q_k + \ldots (D_\mu H)^\dagger (D^\mu H) - \mu^2 H^\dagger H - \frac{\lambda}{4!}(H^\dagger H)^2 + \ldots Y_{k\ell} \overline{Q}_k H (u_R)_\ell$$

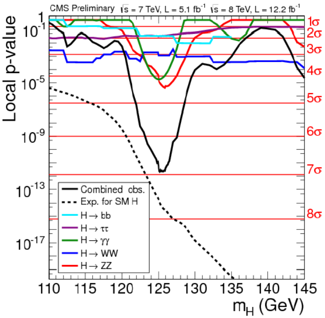
Spontaneous symmetry breaking

- $H \to H' + \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$
- $\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \to \mathrm{U}(1)_Q$
- $A, W^3 \to \gamma, Z^0$ and $W^1_\mu, W^2_\mu \to W^+, W^-$
- Fermions acquire mass through Yukawa couplings to Higgs

The Standard Model

04. July 2012 (13. December 2011)

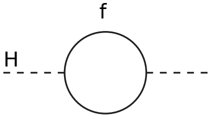
"A new particle that is consistent with the SM Higgs boson"



The Standard Model

We found the Higgs. Why are (most of us) not happy?

1. Funding may be cut off, future of particle physics in danger, ...
2. More importantly: The hierarchy problem



$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}\Lambda_{\rm UV}^2 + \ldots$$

- Higgs mass is quadratically divergent
- Standard Model is renormalizable and infinities can be absorbed into a finite number of physical parameters
- Hierarchy problem arises if one goes beyond renormalizability
  $\rightsquigarrow$ Cut-off Λ_{UV} acquires physical meaning
- Higgs mass is dragged to cut-off scale e.g. $\Lambda_{UV} \sim M_{\rm Planck}$
- As a consequence $m_H \sim M_{\rm Planck}$ (same for m_Z, $m_{W^\pm}$)

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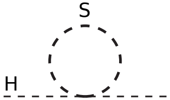
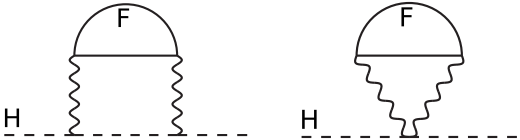


$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}\left[\Lambda_{\mathrm{UV}}^2 - 2m_S^2 \log(\Lambda_{\mathrm{UV}}/m_S) + \dots\right]$$

- What if Λ_{UV} is not physical? Dimensional regularization?
- Any heavy particle that couples to Higgs $\rightsquigarrow$ large corrections
- Even if the coupling is only indirect ...



The Standard Model

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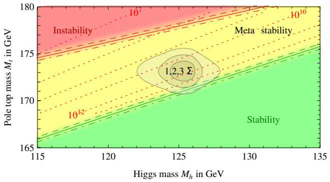
G. Degrassi, S. Di Vita, J. Elias-Miro, J. R. Espinosa, G. F. Giudice, *et al.*, "Higgs mass and vacuum stability in the Standard Model at NNLO," *JHEP* **1208** (2012) 098, 1205.6497

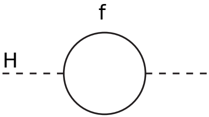


M. Holthausen, K. S. Lim, and M. Lindner, "Planck scale Boundary Conditions and the Higgs Mass," *JHEP* **1202** (2012) 037, 1112.2415

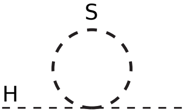
F. Bezrukov, M. Y. Kalmykov, B. A. Kniehl, and M. Shaposhnikov, "Higgs Boson Mass and New Physics," *JHEP* **1210** (2012) 140, 1205.2893

- No new particles between $\rightsquigarrow$ No need for new physics before M_{Planck}
- Connection between EW and Planck scale?

Supersymmetry as a Solution to the Hierarchy Problem



$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}\Lambda_{\rm UV}^2 + \ldots$$

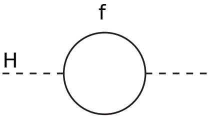


$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}\left[\Lambda_{\rm UV}^2 - 2m_S^2 \log(\Lambda_{\rm UV}/m_S) + \ldots\right]$$

SUSY

- $\lambda_S = |\lambda_f|^2$ and introduces 2 complex scalars for each Dirac fermion
- Quadratic divergences cancel
- Highly predictive, e.g. the SM $\to$ MSSM introduces only 1 new parameter: $\mu H_u H_d$
- Predicts equal superpartner masses $\leadsto$ SUSY breaking
- Predicts fast proton decay $\leadsto$ R-parity

Supersymmetry as a Solution to the Hierarchy Problem



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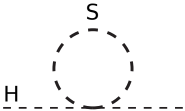


$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}\left[\Lambda_{\rm UV}^2 - 2m_S^2 \log(\Lambda_{\rm UV}/m_S) + \ldots\right]$$

SUSY breaking

- Allow only soft terms, i.e. do not re-introduce hierarchy problem
- Predictivity to some extent lost: SM $\to$ MSSM introduces 104 new parameters
- $\Delta m_H^2 \; = \; m_{\rm soft}^2 \left[\frac{\lambda}{16\pi^2} \log(\Lambda_{\rm UV}/m_{\rm soft}) + \ldots\right]$
- Do not re-introduce hierarchy problem $\rightsquigarrow$ $m_{\rm soft}$ "small"
- What does it mean, "small"? Where can we expect the SUSY sparticles?

Natural SUSY

EWSB condition (for $\tan\beta \gg 1$)

$$m_Z^2 = -2(m_{H_u}^2 + |\mu|^2) + \frac{2}{\tan^2\beta}(m_{H_d}^2 - m_{H_u}^2) + \mathcal{O}\left(\frac{1}{\tan^4\beta}\right)$$

- μ-problem
  Why are SUSY and SUSY breaking parameters of the same order?

- Assume μ is set by soft terms and this is not a problem.
  Typically, $m_{H_u}, |\mu| \gg m_Z$. Why these miraculous cancellations?

- Natural SUSY
  R. Barbieri and G. Giudice, "Upper Bounds on Supersymmetric Particle Masses," *Nucl.Phys.* **B306** (1988) 63

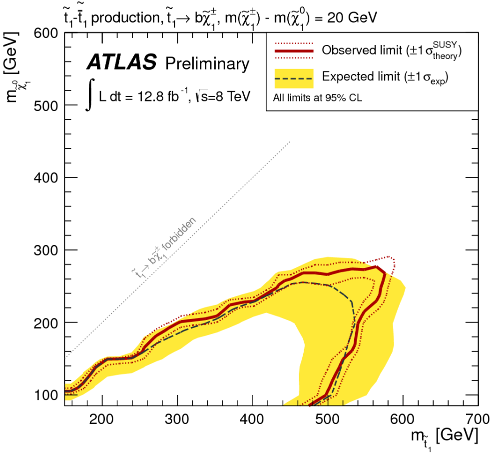
  SUSY spectrum should be "light" such that EWSB need not be "tuned"
  $\rightsquigarrow$ stops, gluinos ($\leftrightarrow m_{H_u}$) and Higgsinos ($\leftrightarrow \mu$) should be light

- Note, however, that this argument goes beyond the hierarchy problem

- Also, note that stops should be heavy enough such that $m_h \gg m_Z$

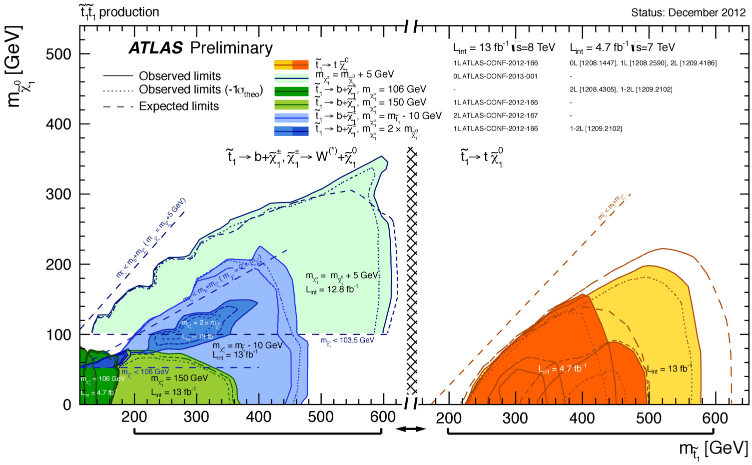
Typical SUSY Exclusion Plot

"Search for direct stop production in events with missing transverse momentum and two b-jets using 12.8 fb^{-1} of pp collisions at $\sqrt{s} = 8$ tev with the atlas detector," Tech. Rep. ATLAS-CONF-2013-001, CERN, Geneva, Jan, 2013



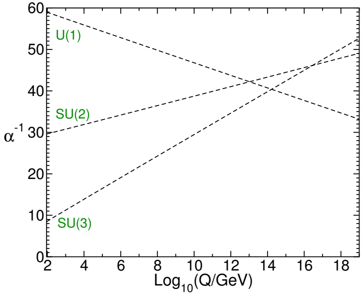
Typical SUSY Exclusion Plot

ATLAS Combined SummaryPlots, Susy Direct Stop Summary

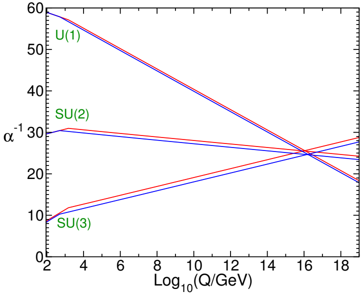


"Experimental" Hints for SUSY?

S. P. Martin, "A Supersymmetry primer," hep-ph/9709356



NO SUSY

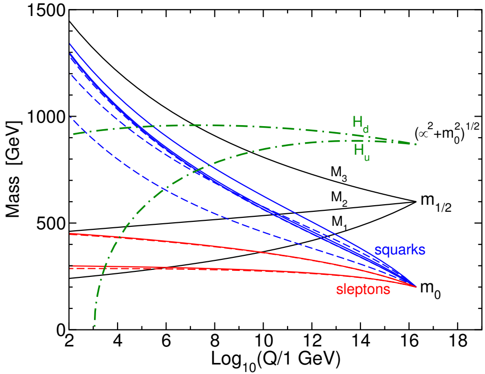


SUSY

- This is an argument in favor of SUSY independent of mSUGRA/cMSSM!
- Requires superparticle masses around 1 TeV?
- Bad news: Not sensitive to scalar masses

mSUGRA/cMSSM

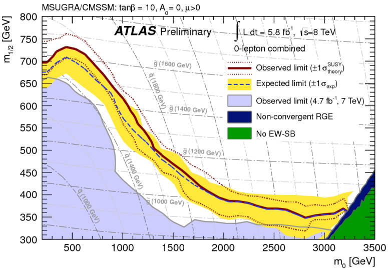
S. P. Martin, "A Supersymmetry primer," hep-ph/9709356



Very economical: Reduces the 105 parameters of SUSY to 5
Very elegant: Radiative electroweak symmetry breaking
Very predictive: Excluded?

mSUGRA/cMSSM

ATLAS-CONF-2012-109



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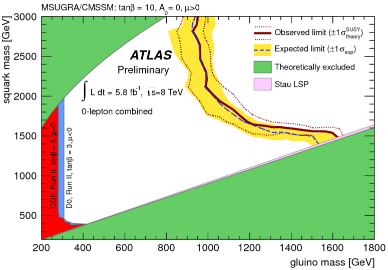

- mSUGRA excluded by LHC data?
- Higgs mass pushes best-fit point to larger $m_{1/2}$ & $\tan\beta \sim 50$ (no $g_\mu - 2$)
- Are SUSY models falsifiable?
- mSUGRA maybe too simplistic?
- Generalize boundary conditions at the GUT scale

mSUGRA/cMSSM

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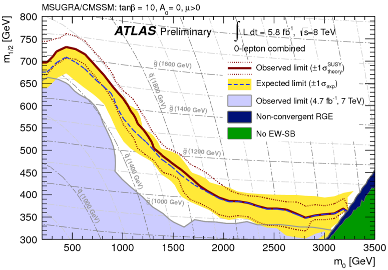
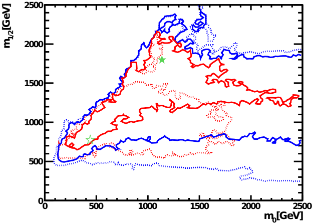


O. Buchmueller et al. arXiv:1112.3564



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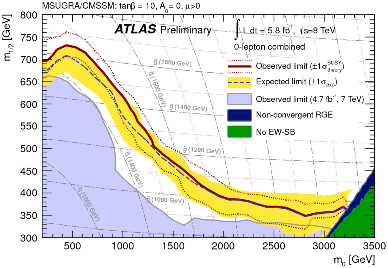

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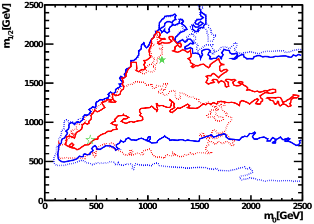

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Let's Stay with GUTs

- There seems to be motivation for a Grand Unified Theory $\sim 10^{16}$ GeV
  1. Gauge coupling unification
  2. Particles organized in a single representation

$$\mathbf{16} = \underset{Q}{(\mathbf{3},\mathbf{2})_{1/3}} + \underset{\bar{u}}{(\overline{\mathbf{3}},\mathbf{1})_{-4/3}} + \underset{\bar{e}}{(\mathbf{1},\mathbf{1})_{-2}} + \underset{\bar{d}}{(\overline{\mathbf{3}},\mathbf{1})_{2/3}} + \underset{L}{(\mathbf{1},\mathbf{2})_{-1}} + \underset{\bar{\nu}}{(\mathbf{1},\mathbf{1})_{0}}$$

  3. "Predicts" right-handed neutrino, hypercharges, B-L

- Consider $\mathrm{SO}(10)$ SUSY GUT, e.g. Dermisek-Raby model
  R. Dermisek and S. Raby, "Bi-large neutrino mixing and CP violation in an SO(10) SUSY GUT for fermion masses," *Phys.Lett.* **B622** (2005) 327–338, hep-ph/0507045

  24 parameters @GUT scale $\rightsquigarrow$ 28 SM and 105 SUSY breaking parameters

- Fit to 36 low-energy observables (includes m_h, θ_{13}, $B_s \to \mu^+\mu^-$, ...)
  A. Anandakrishnan, S. Raby, and A. Wingerter, "Yukawa Unification Predictions for the LHC," 1212.0542

- Third-family Yukawa unification $\lambda\, \mathbf{16}_3 \mathbf{16}_3 \mathbf{10}_H$ implies large $\tan\beta$
  $\lambda_t \simeq \lambda_b \simeq \lambda_\tau$ and $m_t \gg m_b, m_\tau \rightsquigarrow \tan\beta \simeq 50$

Rare Decays

12. November 2012

LHCb Collaboration, R. Aaij *et al.*, "First evidence for the decay $B_s \to \mu^+\mu^-$," 1211.2674

$$\mathcal{B}^{\rm exp}(B_s \to \mu^+\mu^-) = 3.2^{+1.5}_{-1.2} \times 10^{-9}$$
$$\mathcal{B}^{\rm SM}(B_s \to \mu^+\mu^-) = (3.54 \pm 0.30) \times 10^{-9}$$

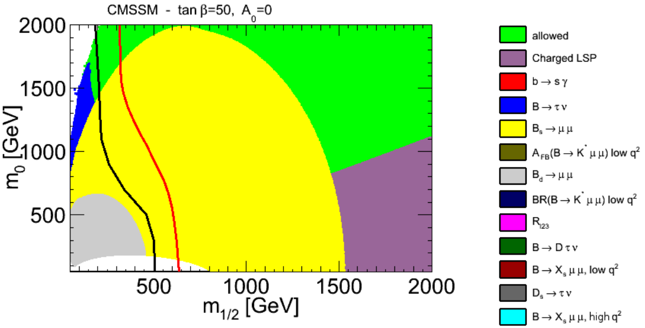
- $B_s \to \mu^+\mu^-$ highly supressed in SM $\leadsto$ Powerful probe for BSM
- Very clear signature, hence high sensitivity (also in hadronic collisions)
- Contribution from SUSY

$$\mathcal{B}(B_s \to \mu^+\mu^-) \propto \frac{\tan^2\beta}{\cos^4\beta}\frac{1}{m_A^4} \sim \frac{\tan^6\beta}{m_A^4} \quad (\text{ for } \tan\beta \gg 1)$$

- Constrains models with large $\tan\beta$
  - $\tan\beta \gg 1$ implies $m_A \gg 1$
  - Leads to Higgs decoupling limit (e.g. in DR-model)

Rare Decays

T. Hurth and F. Mahmoudi, "New physics search with flavour in the LHC era," 1211.6453



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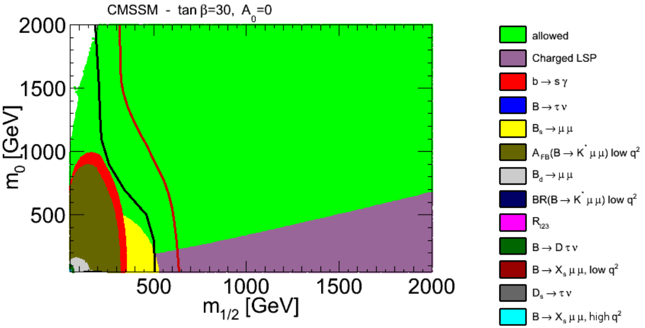
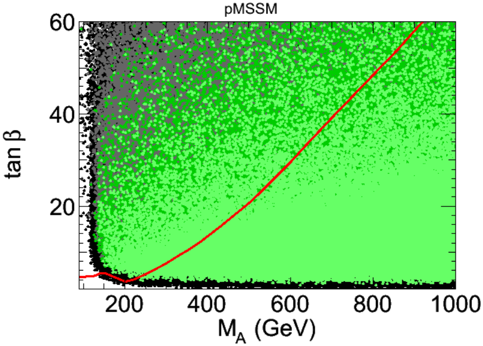


Rare Decays

A. Arbey, M. Battaglia, F. Mahmoudi, and D. M. Santos, "Supersymmetry confronts $B_s \to \mu^+\mu^-$: Present and future status," 1212.4887

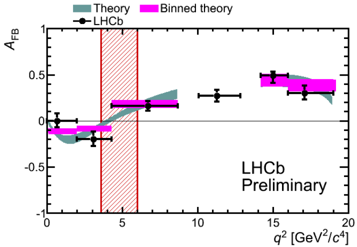


Valid pMSSM, $123 < m_H < 129$, $\mathcal{B}^{\rm exp}(B_s \to \mu^+\mu^-)$ current and future

Rare Decays

Skipping due to time constraints other LHCb highlights of 2012:

- $B_d \to K^* \mu^+ \mu^-$ LHCb-CONF-2012-008



- Limits on $K_S^0 \to \mu^+ \mu^-$
- B and D oscillations

What I did not find the time to talk about . . .

- SUSY breaking scenarios
  Gauge mediation, anomaly mediation, . . .
  (All aim at reducing #parameters)
- NMSSM: Addresses the μ-problem, eases tension $m_h \leftrightarrow m_H^{\mathrm{exp}}$
- $\mu\nu$MSSM: Neutrino masses
- pMSSM: Captures general features of SUSY models
- R-parity violation
- Minimal Flavor Violation

Neutrinos have mass and mix

- Neutrinos have mass and the different flavors can mix

  Super-Kamiokande Collaboration, Y. Fukuda *et al.*, "Evidence for oscillation of atmospheric neutrinos," *Phys. Rev. Lett.* **81** (1998) 1562–1567, hep-ex/9807003

  SNO Collaboration, Q. R. Ahmad *et al.*, "Direct evidence for neutrino flavor transformation from neutral-current interactions in the Sudbury Neutrino Observatory," *Phys. Rev. Lett.* **89** (2002) 011301, nucl-ex/0204008

- Charged lepton and neutrino mass matrices cannot be simultaneously diagonalized

$$\hat{M}_{\ell^+} = D_L M_{\ell^+} D_R^\dagger, \quad \hat{M}_\nu = U_L M_\nu U_R^\dagger$$

- Pontecorvo-Maki-Nakagawa-Sakata matrix

  B. Pontecorvo, "Mesonium and antimesonium," *Sov. Phys. JETP* **6** (1957) 429

  Z. Maki, M. Nakagawa, and S. Sakata, "Remarks on the unified model of elementary particles," *Prog. Theor. Phys.* **28** (1962) 870–880

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{D_L U_L^\dagger}_{U_{\mathrm{PMNS}}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Parametrizing the lepton sector

Pontecorvo-Maki-Nakagawa-Sakata matrix: 3 angles + 1 Dirac phase (+ 2?)

$$U_{\mathrm{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & e^{-i\delta} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta} s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$= \begin{pmatrix} c_{12} c_{13} & s_{12} c_{13} & s_{13} e^{-i\delta} \\ -c_{23} s_{12} - s_{13} s_{23} c_{12} e^{i\delta} & c_{23} c_{12} - s_{13} s_{23} s_{12} e^{i\delta} & s_{23} c_{13} \\ s_{23} s_{12} - s_{13} c_{23} c_{12} e^{i\delta} & -s_{23} c_{12} - s_{13} c_{23} s_{12} e^{i\delta} & c_{23} c_{13} \end{pmatrix}$$

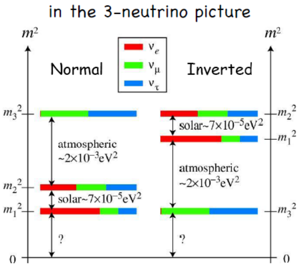
Charged and neutral lepton mass matrices: 3 charged + 3 neutral lepton masses

$$\hat{M}_{\ell^+} = \begin{pmatrix} m_e & 0 & 0 \\ 0 & m_\mu & 0 \\ 0 & 0 & m_\tau \end{pmatrix}, \qquad \hat{M}_\nu = \begin{pmatrix} m_{\nu_1} & 0 & 0 \\ 0 & m_{\nu_2} & 0 \\ 0 & 0 & m_{\nu_3} \end{pmatrix}$$

What we know . . .

M. Gonzalez-Garcia, M. Maltoni, J. Salvado, and T. Schwetz, "Three-neutrino results after Neutrino 2012 Conference." http://www.nu-fit.org, 2012

Parameter	Best Fit	3σ range	Comments
$\theta_{12}[^\circ]$	33.3 ± 0.8	$31 - 36$	best-known angle
$\theta_{23}[^\circ]$	$40.0^{+2.1}_{-1.5} \oplus 50.4^{+1.2}_{-1.3}$	$36 - 55$	$> 45^\circ$ or $< 45^\circ$?
$\theta_{13}[^\circ]$	$8.6^{+0.44}_{-0.46}$	$7.2 - 9.5$	NEW!
$m^2_{21}[\mathrm{eV}^2]$	$(7.50 \pm 0.185) \times 10^{-5}$	$(7.00 - 8.09) \times 10^{-5}$	> 0!
$m^2_{31}[\mathrm{eV}^2]$	$(2.47^{+0.069}_{-0.067}) \times 10^{-3}$	$(2.27 - 2.69) \times 10^{-3}$	> 0 or < 0?
$m^2_{32}[\mathrm{eV}^2]$	$(-2.43^{+0.042}_{-0.065}) \times 10^{-3}$	$((-2.65) - (-2.24)) \times 10^{-3}$	fixed



$$U_{\mathrm{PMNS}} = \begin{pmatrix} 0.795-0.846 & 0.513-0.585 & 0.126-0.178 \\ 0.205-0.543 & 0.416-0.730 & 0.579-0.808 \\ 0.215-0.548 & 0.409-0.725 & 0.567-0.800 \end{pmatrix}$$

Why may neutrino masses indicate new physics?

- Introduce right-handed neutrino ν_R and assume it is Dirac

$$\mathcal{L}_Y = Y^U_{k\ell} Q_k H^c (u_R)_\ell + Y^D_{k\ell} Q_k H (d_R)_\ell + Y^E_{k\ell} L_k H (e_R)_\ell + Y^\nu_{k\ell} L_k H^c (\nu_R)_\ell$$

- In principle, nothing wrong with that
- Absolute mass scale of neutrinos not known, but e.g.

$$m_3^2, m_1^2 \overset{!}{\gtrsim} \Delta m^2_{31} = 2.47 \times 10^{-3} \mathrm{eV}^2 \quad \text{and} \quad \sum m_i \lesssim 1 \mathrm{eV}$$

(arXiv:1103.5083)

- Yukawas need to span (at least) 9 orders of magnitude

$$\frac{m_\tau}{m_\mu} \sim 17, \quad \frac{m_\tau}{m_e} \sim 3477, \quad \frac{m_t}{m_b} \sim 41, \quad \frac{m_t}{m_u} \sim 10^5, \quad \frac{m_\tau}{m_\nu} \sim 10^9$$

Type-I Seesaw

P. Minkowski, "$\mu \to e\gamma$ at a Rate of One Out of 1-Billion Muon Decays?," *Phys. Lett.* **B67** (1977) 421

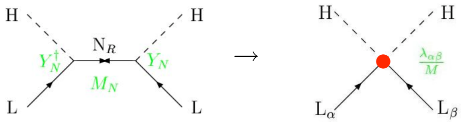
For simplicity, assume 1 generation: $\mathcal{L}_Y = y_\nu L H^c \nu_R + M \nu_R \nu_R$

$$M_{\ell^+} = \begin{array}{c c} & \begin{array}{cc} \nu_L & \nu_R \end{array} \\ \begin{array}{c} \nu_L \\ \nu_R \end{array} & \begin{pmatrix} 0 & y_\nu v \\ y_\nu v & M \end{pmatrix} \end{array} \quad \rightsquigarrow \quad m_1 \simeq \frac{y_\nu^2 v^2}{M}, \; m_2 \simeq M$$

Some remarks:

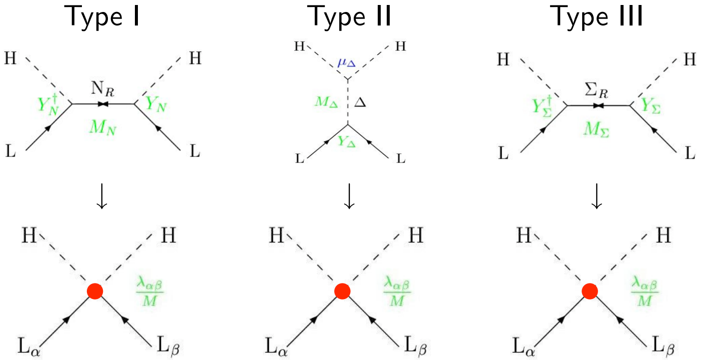
- Remember that ν_R is a "prediction" of $\mathrm{SO}(10)$
- Substituting some numbers that make sense:
  $y_\nu \sim 1$, $v = 246$ GeV, $M \sim 10^{15}$ GeV $\rightsquigarrow m_1^2 \simeq 3 \times 10^{-3} \mathrm{eV}^2$
- Second mass eigenstate super heavy $\rightsquigarrow$ No LHC phenomenology
- Type-I seesaw reduces to dimension-5 operator in effective theory

Shamelessly stolen from Thomas Hambye's talk



Other Seesaw Mechanisms

Shamelessly stolen from Thomas Hambye's talk



- All lead to same dimension-5 (!) operator *LLHH*
- Couplings determined by mass of particle that is integrated out
- LHC phenomenology depends on model assumptions

Yet another seesaw mechanism

Inverse (or double) seesaw mechanism

R. Mohapatra and J. Valle, "Neutrino Mass and Baryon Number Nonconservation in Superstring Models," *Phys.Rev.* **D34** (1986) 1642

- Seesaw + GUTs: Need large representations like **120** or **126**
- Not present in string theory compactifications
- Invented to cure this problem (embedding $\mathrm{SO}(10) \hookrightarrow$ strings)
- Potential LHC phenomenology

E.g. the Dermisek-Raby model and its recent fit to data

A. Anandakrishnan, S. Raby, and A. Wingerter, "Yukawa Unification Predictions for the LHC," 1212.0542

- Inverse seesaw
- Family symmetry $D_3 \times \mathbb{Z}_2 \times \mathbb{Z}_3$ at GUT scale
- Fits neutrino masses and angles: $\theta_{13} \simeq 6^\circ$

Discrete Flavor Symmetries

Reverse engineering

$$W = y_e \frac{\widetilde{\varphi}}{\Lambda} L e h_d + y_\mu \frac{\widetilde{\varphi}}{\Lambda} L \mu h_d + y_\tau \frac{\widetilde{\varphi}}{\Lambda} L \tau h_d + y_1 \frac{\widetilde{\varphi}}{\Lambda^2} L L h_u h_u + y_2 \frac{\varphi}{\Lambda^2} L L h_u h_u$$

- Consider effective Lagrangian (seesaw mechanism implicit)
- Mass hierarchy & mixing generated by flavon fields
- Neutrino masses suppressed w.r.t. charged lepton masses
- Λ is scale of "fundamental" physics and in principle determined by UV completion
- Family symmetry and flavon vevs determine mixing angles

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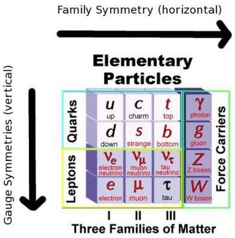
Discrete Flavor Symmetries



❶ Symmetries of the model

$$\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \times T_7 \times \mathrm{U}(1)_R$$

❷ Particle content and charges

Field	$\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$	T_7	$\mathrm{U}(1)_R$
L	$(\mathbf{2}, -1)$	$\mathbf{3}$	1
e	$(\mathbf{1}, 2)$	$\mathbf{1}$	1
μ	$(\mathbf{1}, 2)$	$\mathbf{1}'$	1
τ	$(\mathbf{1}, 2)$	$\mathbf{1}''$	1
h_u	$(\mathbf{2}, 1)$	$\mathbf{1}$	0
h_d	$(\mathbf{2}, -1)$	$\mathbf{1}$	0
φ	$(\mathbf{1}, 0)$	$\mathbf{3}$	0
$\widetilde{\varphi}$	$(\mathbf{1}, 0)$	$\mathbf{3}'$	0

❸ Breaking the family symmetry

$$\langle\varphi\rangle = (v_\varphi, v_\varphi, v_\varphi), \quad \langle\widetilde{\varphi}\rangle = (v_{\widetilde{\varphi}}, 0, 0)$$

$$W = y_e \frac{\widetilde{\varphi}}{\Lambda} L e h_d + y_\mu \frac{\widetilde{\varphi}}{\Lambda} L \mu h_d + y_\tau \frac{\widetilde{\varphi}}{\Lambda} L \tau h_d + y_1 \frac{\widetilde{\varphi}}{\Lambda^2} L L h_u h_u + y_2 \frac{\varphi}{\Lambda^2} L L h_u h_u$$

$$M_{\ell^+} = -\frac{v_d v_{\widetilde{\varphi}}}{\sqrt{6}\Lambda} \times \begin{array}{c} \\ L_1^{(2)} \\ L_2^{(2)} \\ L_3^{(2)} \end{array} \begin{array}{c} \begin{array}{ccc} e & \mu & \tau \end{array} \\ \begin{pmatrix} y_e & 0 & 0 \\ 0 & y_\mu & 0 \\ 0 & 0 & y_\tau \end{pmatrix} \end{array}$$

$$M_\nu = \frac{v_u^2}{12\Lambda^2} \times \begin{array}{c|ccc} & L_1^{(1)} & L_2^{(1)} & L_3^{(1)} \\ \hline L_1^{(1)} & \sqrt{2}y_2 v_\varphi + 2y_1 v_{\widetilde{\varphi}} & -\frac{1}{2}\sqrt{2}y_2 v_\varphi & -\frac{1}{2}\sqrt{2}y_2 v_\varphi \\ L_2^{(1)} & -\frac{1}{2}\sqrt{2}y_2 v_\varphi & \sqrt{2}y_2 v_\varphi & -\frac{1}{2}\sqrt{2}y_2 v_\varphi + 2y_1 v_{\widetilde{\varphi}} \\ L_3^{(1)} & -\frac{1}{2}\sqrt{2}y_2 v_\varphi & -\frac{1}{2}\sqrt{2}y_2 v_\varphi + 2y_1 v_{\widetilde{\varphi}} & \sqrt{2}y_2 v_\varphi \end{array}$$

$\theta_{12} = 35.26^\circ$, $\theta_{23} = 45^\circ$, $\theta_{13} = 0^\circ$

Discrete Flavor Symmetries

Why do we think that there might be a family symmetry?

$$U_{\mathrm{PMNS}}^{\mathrm{exp}} \stackrel{?}{=} U_{\mathrm{HPS}}$$

$$U_{\mathrm{PMNS}}^{\mathrm{exp}} = \begin{pmatrix} 0.795-0.846 & 0.513-0.585 & 0.126-0.178 \\ 0.205-0.543 & 0.416-0.730 & 0.579-0.808 \\ 0.215-0.548 & 0.409-0.725 & 0.567-0.800 \end{pmatrix}$$

$$U_{\mathrm{HPS}} = \begin{pmatrix} 0.816 & 0.577 & 0 \\ 0.408 & 0.577 & 0.707 \\ 0.408 & 0.577 & 0.707 \end{pmatrix} = \begin{pmatrix} \sqrt{2/3} & 1/\sqrt{3} & 0 \\ -1/\sqrt{6} & 1/\sqrt{3} & -1/\sqrt{2} \\ -1/\sqrt{6} & 1/\sqrt{3} & 1/\sqrt{2} \end{pmatrix}$$

- Form of U_{HPS} suggests existence of a symmetry
  P. F. Harrison, D. H. Perkins, and W. G. Scott, "Tri-bimaximal mixing and the neutrino oscillation data," *Phys. Lett.* **B530** (2002) 167, hep-ph/0202074
- Daya bay and Reno measure $\theta_{13} \simeq 9^\circ$ **08. March 2012**
  arXiv:1203.1669, arXiv:1204.0626
- Tribimaximal mixing pattern excluded (at least @LO)

Discrete Flavor Symmetries

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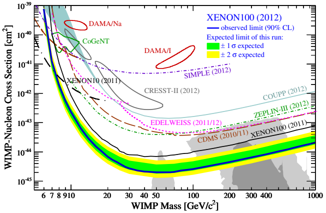
- Long-cherished “paradigm” $A_4 \leftrightarrow U_{\text{HPS}}$ in bad shape
- Any regular structure suggests underlying symmetry!
- Look for groups that give $\theta_{13} \neq 0^\circ$

  R. d. A. Toorop, F. Feruglio, and C. Hagedorn, “Discrete Flavour Symmetries in Light of T2K,” *Phys.Lett.* **B703** (2011) 447–451, 1107.3486

Direct Dark Matter Searches

18. July 2012

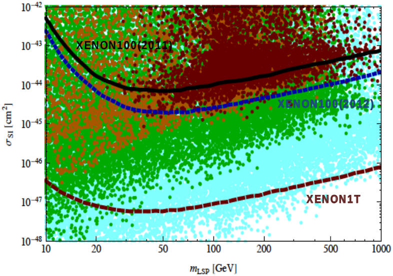
XENON100 Collaboration Collaboration, E. Aprile *et al.*, "Dark Matter Results from 225 Live Days of XENON100 Data," *Phys.Rev.Lett.* **109** (2012) 181301, 1207.5988



- ➢ No dark matter particle(s) discovered as of today
- ➢ Not compatible with DAMA or CoGeNT (see P. Serpico's talk)
- ➢ Xenon100 (indirectly) probes SUSY parameter space
- ➢ Upgrade to Xenon1T planned

Dark Matter + MSSM

M. Perelstein and B. Shakya, "XENON100 Implications for Naturalness in the MSSM, NMSSM and lambda-SUSY," 1208.0833

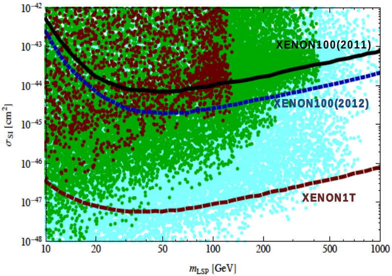


$p \equiv$ min(Higgsino, gaugino fraction) "purity"

- Red: $p > 0.2$
- Orange: $0.1 < p < 0.2$
- Green: $0.01 < p < 0.1$
- Cyan: $10^{-3} < p < 0.01$

Dark Matter + MSSM + Naturalness

M. Perelstein and B. Shakya, "XENON100 Implications for Naturalness in the MSSM, NMSSM and lambda-SUSY," 1208.0833



Fine-tuning Δ at EW scale ("Naturalness"):

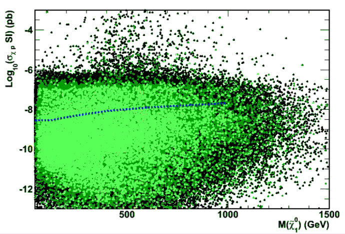
- Red: $0 < \Delta < 10$
- Green: $10 \leq \Delta < 100$
- Cyan: $100 \leq \Delta < 1000$

Dark Matter + pMSSM

Talk by A. Arbey at conference "Neutrinos at the forefront of elementary particle physics and astrophysics", 2012

Dark Matter direct detection and pMSSM

pMSSM points and XENON dark matter exclusion limit



A. Arbey, M. Battaglia, A. Djouadi, F. Mahmoudi, to appear

Black: valid points passing the relic density, flavour physics, LHC SUSY search, LEP and Tevatron constraints

Dark green: points also compatible at 90% C.L. with the LHC Higgs search results
Light green: points also compatible at 68% C.L. with the LHC Higgs search results

Dotted blue line: 2012 XENON-100 limit at 95% C.L.

28% of the valid points are excluded by XENON-100

Alexandre Arbey Supersymmetric Dark Matter

Sterile Neutrinos

Just mentioning in passing (see talk by S. Davidson) ...

- Number of (light) neutrino generations from cosmology
- Cosmology does not constrain #neutrinos with $m_\nu \gtrsim$ keV
- Hints for sterile neutrinos (WMAP, reactor flux, ...), but:
  1. Statistically not significant
  2. "Who ordered that?" It is not the ν_R of type-I seesaw!
- For neutrino masses,

$$\sum m_{\nu_i} \lesssim 1 \text{ eV}$$

  is safe; more stringent bounds entail more assumptions
- Planck collaboration to release data this year. Really excited!

Conclusions

- In terms of experimental results, 2012 has been an exciting year!
- Many theoretical arguments that SM may not be the final word
- However, scale of new physics unclear (no really good arguments)
- SUSY
  - Still at large. Good news: Not excluded either
  - No clear idea where the SUSY breaking scale should be
  - Could have shown up in many places
  - Whether disfavored/hospitalized or not is not clear (subjective)
- Some ("experimental") hints for GUTs; solve many problems; introduce new ones
- Situation at neutrino frontier unclear; A_4 has died; sterile neutrinos show up
- Interplay between colliders ↔ flavor physics ↔ dark matter/cosmology may bring first hint of (really) new physics