Supersymmetry without prejudice. When?

Shehu S. AbdusSalam

ICTP, Trieste

SUSY2013, ICTP, Trieste
30 August, 2013

This talk is mainly based on:

work done in collaboration with
B.C.Allanach, D.Choudhury, F.Quevedo, F.Feroz and M.Hobson
arXiv:0809.0284, 0904.2548, 1210.3331, 1211.0999

and work in progress with F.Quevedo and C.Burgess

Towards MSSM-124 phenomenology

Time: Steps	Some, key references
1998, 1999: pMSSM @ GDR 1998	MSSM WG, hep-ph/9901246
2004: Random sampling of pMSSM-20	S.Profumo, C.E.Yaguna hep-ph/0407036
SUSY-2008: Statistically convergent pMSSM-25 sampling & fit to data	SS.A, BC.Allanach, F.Quevedo, et. al. 0809.0284, 0904.2548
After SUSY-2008: Lot more Random samplings of pMSSM parameters	Various groups Lots of papers & citations
2008: MFV MSSM reparametrisation $\mathcal{O}(\lambda_{CB}^n)$ parameters rating	G.Colangelo, E.Nikolidakis, C.Smith, 0807.0801
Today: MSSM-42, MSSM-30, MSSM-24, CMSSM-9.	SS.A, F.Quevedo, C.Burgess, S.S.A. SUSY-2013 talk

Supersymmetry is without prejudice when,

Theory:
(1) Model and assumptions to conclusions are explicit.

Phenomenology:
(2) Ad hoc and unnecessary simplifications are as minimal as possible.
(3) Robust methodologies are used: compare nested, MCMC and random samplings.

Experiments:
(4) Usable model-independent results are published. Trigger systems.
(5) Full likelihood functions are at least used by the collaborations themselves, published or to working groups.

Table of Contents

Supersymmetry prejudice(P) examples

Minimal gauge group and particles content, R-parity, $m_\nu = 0$, get minimal, 124 parameters MSSM.

pMSSM-25 = MSSM-124 - extra{CP-violating, FCNC} & SM-14

- P: CMSSM-5 conclusions are representing the MSSM
- P: pMSSM-25 is not MFV; flavour physics constraints
- P: Outcomes of random scans (10^{248} points sample??)

Naturalness means minimal fine-tuning. Model, assumptions and fine-tuning measures (Δ_{EW} or Δ_{BG}) should be specified.

- P: $m^2_{\tilde{t}_L} \simeq m^2_{\tilde{b}_L} \simeq m^2_{\tilde{t}_R} \lesssim 700\ \mathrm{GeV}$, heavy $m_{\tilde{g}}$ and $m_{\tilde{q}}^{1st/2ndgen}$
- P: $(m_{\tilde{b}_1}, m_{\tilde{b}_2}, m_{\tilde{g}}, m_{\tilde{q}_{1,2}}) = (1, 1.1, 2, \mathcal{O}(10))\ \mathrm{TeV}$
- P: SUSY bull's eye, Natural SUSY is cornered

MFV MSSM reparametrisation

(A) 0807.0801: MFV in the MSSM $\equiv$ reparametrisation of SUSY-breaking terms, in $(Y_U^\dagger Y_U)_{ij}$ and $(Y_D^\dagger Y_D)_{ij}$ basis,

$$(M_Q^2)_{ij} = m^2 \left[a_1 \delta_{ij} + b_1 (Y_U^\dagger Y_U)_{ij} + b_2 (Y_D^\dagger Y_D)_{ij} + \ldots \right]. \quad (1)$$

(B) Freeze spurions to physical values, use new MFV basis, counting and selection of parameters rules to get

- MSSM-42 at $\mathcal{O}(\lambda_{CB}^6) \sim 10^{-4}$
- MSSM-30 at $\mathcal{O}(\lambda_{CB}^4) \sim 10^{-3}$
- MSSM-24 at $\mathcal{O}(\lambda_{CB}^3) \sim 10^{-2}$

(C) Constrain the models by using all possible data,

$$\begin{aligned} \underline{d} &= d_{non-LHC} \oplus d_{LHC-SUSY} \oplus d_{LHC-others} \oplus d_{\Delta_{EW}} && (2) \\ &= \{\mu_i, \sigma_i\} \oplus \ldots \oplus \{\Delta_{EW}^{-1} \geq 5\%\} && (3) \end{aligned}$$

Minimal flavour violation and new basis

(A) Collapse eq.(1) to few terms by Cayley-Hamilton identities

(B) large pieces of $(Y_U^\dagger Y_U)^2_{ij}, (Y_U^\dagger Y_U)_{ij} \propto V^*_{3i} V_{3j}$, small pieces to $V^*_{2i} V_{2j}$, So use $V^*_{3i} V_{3j}$ and $V^*_{2i} V_{2j}$ with coefficients of order one and $y_c^2 \sim \lambda^8$ respectively.

(C) Similarly for $(Y_D^\dagger Y_D)_{ij}$ and $(Y_D^\dagger Y_D)^2_{ij}$, use $\delta^*_{i3}\delta_{j3}$ and $\delta^*_{i2}\delta_{j2}$ with order y_b^2 and y_s^2 coefficients respectively

(D) All possible multipliable structures lead to new complete basis vectors $X_1 = \delta^*_{i3}\delta_{j3}, \ldots, X_{16} = V^*_{2i} V_{3j}$

MSSM-42, MSSM-30, MSSM-24, CMSSM-9

$$
\begin{aligned}
e^{\phi_1}M_1, \quad e^{\phi_2}M_2, \quad M_3, \quad \mu, \quad M_A, \quad \tan\beta, \quad e^{\phi_\mu}, \\
M_Q^2 &= \tilde{a}_1 + x_1 X_{13} + y_1 X_1 + y_2 X_5 + y_2^* X_9, \\
M_U^2 &= \tilde{a}_2 + x_2 X_1, \\
M_D^2 &= \tilde{a}_3 + y_3 X_1 + w_1 X_3 + w_1^* X_4, \\
M_L^2 &= \tilde{a}_6 + y_6 X_1, \\
M_E^2 &= \tilde{a}_7 + y_7 X_1, \\
A_E &= \tilde{a}_8 X_1 + w_5 X_2, \\
A_U &= \tilde{a}_4 X_5 + y_4 X_1 + w_2 X_6, \\
A_D &= \tilde{a}_5 X_1 + y_5 X_5 + w_3 X_2 + w_4 X_4
\end{aligned}
\tag{4}
$$

$\tilde{a}_{1-3,6,7} > 0, x_1, x_2, y_1, y_3, y_6, y_7 \in \mathbb{R}$ others are complex.
MSSM-30: use $\tilde{a}_{1-3,6,7} > 0, x_1, x_2, y_1, y_3, y_6, y_7 \in \mathbb{R},\ y_4, y_5 \in \mathbb{C}$
MSSM-24: use $\tilde{a}_{1-3,6,7} > 0, x_1, x_2 \in \mathbb{R},\ y_5 \in \mathbb{C}$ (reduce to CMSSM-9.)

MFV X_i basis matrices

$$X_1 = \delta_{3i}\delta_{3j}\,, \quad X_2 = \delta_{2i}\delta_{2j}\,, \quad X_3 = \delta_{3i}\delta_{2j}\,, \quad X_4 = \delta_{2i}\delta_{3j}\,, \tag{5}$$

$$X_5 = \delta_{3i}V_{3j}\,, \quad X_6 = \delta_{2i}V_{2j}\,, \quad X_7 = \delta_{3i}V_{2j}\,, \quad X_8 = \delta_{2i}V_{3j}\,, \tag{6}$$

$$X_9 = V^*_{3i}\delta_{3j}\,, \quad X_{10} = V^*_{2i}\delta_{2j}\,, \quad X_{11} = V^*_{3i}\delta_{2j}\,, \quad X_{12} = V^*_{2i}\delta_{3j}\,, \tag{7}$$

$$X_{13} = V^*_{3i}V_{3j}\,, \quad X_{14} = V^*_{2i}V_{2j}\,, \quad X_{15} = V^*_{3i}V_{2j}\,, \quad X_{16} = V^*_{2i}V_{3j}\,. \tag{8}$$

V is the CKM matrix

Bayes theorem, testing data strength

- **Bayes theorem:**
  posterior = likelihood $\times$ prior / (evidence)
  $P(\theta|\underline{d}, H) = P(\underline{d}|\theta, H)\, P(\theta, H) \;/\; P(\underline{d}, H)$

- **Prior-dependence & prior-independence:**
  (1) Prior-independent results = prediction
  (2) Prior-dependence = prediction, also
  (3) Possibility, test data strength: precise & robust

Prior-dependence & prior-independence examples

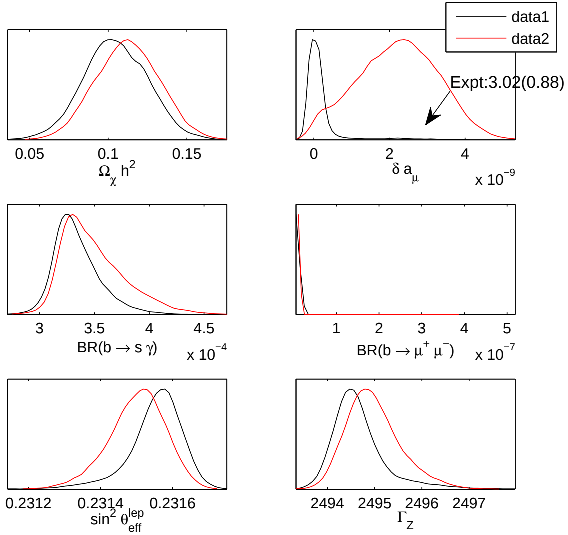


Figure: (data2, data1) curves = (log-, flat-) prior fit.

pMSSM-25 predictions

- **2008/9-fit:**
  (1) $m_h \sim 117 - 129\ \mathrm{GeV}$ @ 95% BC,
  (2) $BR(B_s \to \mu^+ \mu^-) \sim 0.28 \times 10^{-8}$
  (3) $m_{\tilde{t}_1} \sim 1 - 3\ \mathrm{TeV}$,
  (4) undetermined $m_{\tilde{g}}, m_{\tilde{q}_o}, (g-2)_\mu$

pMSSM-25 predictions, Natural SUSY

- **2013-fit, Δ_{EW}-data included:**
  (1) $m_{\tilde{t}_1} \sim 1-2\ \mathrm{TeV}, m_{\tilde{\chi}^0_{1,2}} \sim m_{\tilde{\chi}^\pm_1} \lesssim 600\ \mathrm{GeV}$
  (2) under-abundance of $\tilde{\chi}^0_1$ LSP CDM

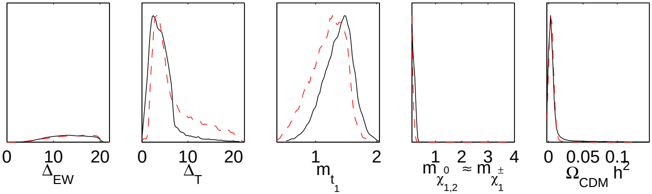
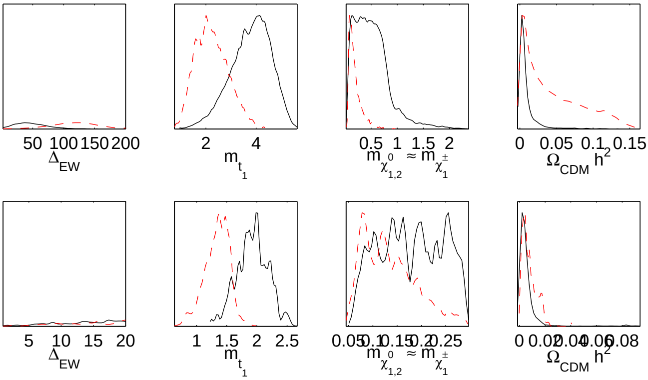


Figure: (Δ_{EW}, Δ_T) fine-tuning measures in (eq.(9), eq.(11)). (Dotted, solid) curves = (log-, flat-) prior. Masses in TeV units.

MSSM-42, MSSM-30 status

- **Spectra properties:** SPheno & SUSY_FLAVOUR, 30- or 42-parameters MSSM in SLHA-2 format; MultiNest
- **MSSM-30 test fit:**

(1) undetermined $m_{\tilde{t}_1}, m_{\tilde{g}}, m_{\tilde{q}_o}, m_{\tilde{\chi}_i^0}, m_{\tilde{\chi}_i^\pm}, (g-2)_\mu, \ldots$.



(2) under-abundance of $\tilde{\chi}_1^0$ LSP CDM

Conclusions & Outlook

Supersymmetry without prejudice. When?

Supersymmetry is without prejudice when,

Theory:
(1) Model and assumptions to conclusions are explicit.

Phenomenology:
(2) Ad hoc and unnecessary simplifications are as minimal as possible.
(3) Robust methodologies are used: compare nested, MCMC and random samplings.

Experiments:
(4) Usable model-independent results are published. Trigger systems.
(5) Full likelihood functions are at least used by the collaborations themselves, published or to working groups.

Conclusions & Outlook

- (1) pMSSM-25 away from CMSSM/mSUGRA
  (2) Bayesian methodology 2008/9 and 2013 fits predictions
- (3) MSSM-124, MSSM-42, MSSM-30, away from pMSSM
  (4) pMSSM is never MFV nor a limit of MFV-MSSM
- (5) Less of the global-picture MSSM has been probed
  (6) MSSM-42, MSSM-30 working frames just introduced
- (7) Less than 10% of expected LHC data

  Therefore: MSSM fate & decisive conclusions? Too early.
  But, so far, looks very bright!
  Let's get ready for LHC run-2!!

Thanks for Listening!

Codes for physical observables, sampling and fitting

- **SPheno**: SUSY spectra and low-energy observables calculation from SLHA2 parameters
- **SUSY_FLAVOUR**: Calculates low-energy observables from SLHA2 parameters
- **SOFTSUSY**: SUSY spectra from SLHA1 parameters
- **micrOMEGAs**: CDM relic density, (g-2)
- **superISO**: B-physics observables
- **susyPOPE**: EW precision observables
- **MultiNest**: Nested sampling and Fit

Example, 2008/9 pMSSM-25 probability densities

Parameters, $\theta_{pMSSM-25}$ =
θ_{SM-5}, $\tan\beta$, $m^2_{H_1}$, $m^2_{H_2}$; $M_{1,2,3}$; $m^{3rdgen}_{\tilde{f}_{1,2,3,4,5}}$, $m^{1/2ndgen}_{\tilde{f}_{1,2,3,4,5}}$; $A_{t,b,\tau,\mu=e}$

Priors: $\pi(\theta) = P(\theta) = \pi(\theta_1)\,\pi(\theta_2)\,\ldots\,\pi(\theta_{25})$

Predictions: O_i from 25 input parameters θ_i

$$O = \{ \; m_W,\ \sin^2\theta^{lep}_{eff},\ \Gamma_Z,\ R_{l,b,c},\ A^{c,b}_{\mathrm{FB}},\ A_{l,b,c},\ \delta a_\mu,\ m_h,\ Br(b\to s\gamma),\ BF(B\to\mu^+\mu^-),\ \Delta_{0-},\ Br(B_u\to\tau\nu),\ \Delta M_{B_s},\ \Omega_\chi h^2 \}$$

Data: $D = \{\mu(O_i), \sigma(O_i)\}$

Likelihood:
$P(D|\theta) = \prod_i P(D_i|\theta)$; $\quad P(D_i|\theta) = (2\pi\sigma_i^2)^{-1/2}\, e^{-(O_i-\mu_i)^2/(2\sigma_i^2)}$

MSSM-30 test fit, constraints

Observable	Constraint	Observable	Constraint
m_W [GeV]	80.399 ± 0.027	$A^l = A^e$	0.1513 ± 0.0021
Γ_Z [GeV]	2.4952 ± 0.0025	A^b	0.923 ± 0.020
$\sin^2\ \theta_{eff}^{lep}$	0.2324 ± 0.0012	A^c	0.670 ± 0.027
δa_μ	$(30.2 \pm 9.0) \times 10^{10}$	$Br(B \to X_s\gamma)$	$(3.55 \pm 0.42) \times 10^4$
R_l^0	20.767 ± 0.025	$Br(B_s \to \mu^+\mu^-)$	$3.2 \times 10^{+1.5}_{-1.2}$
R_b^0	0.21629 ± 0.00066	$R_{\Delta M_{B_s}}$	0.85 ± 0.11
R_c^0	0.1721 ± 0.0030	$R_{Br(B_u \to \tau\nu)}$	1.26 ± 0.41
A_{FB}^b	0.0992 ± 0.0016	Δ_{0-}	0.0375 ± 0.0289
A_{FB}^c	0.0707 ± 0.035	$\Omega_{CDM}h^2$	0.11 ± 0.02
		m_h	125.6 ± 3.0 [GeV]

Table: Summary for the central values and errors for the electroweak physics observables, B-physics observables and cold dark matter relic density constraints.

MSSM-30 test fit, constraints

Observable	Constraint	Observable	Constraint
$Br(B \to X_s\gamma)$	$(3.52 \pm 0.25) \times 10^4$	$R_{Br(B_u \to \tau\nu)}$	1.4909 ± 0.309
$Br(B_s \to \mu^+\mu^-)$	$3.2^{+1.5}_{-1.2} \times 10^{-9}$cite	$Br(B_d \to \mu^+\mu^-)$	$> 1.8 \times 10^{-8}$
ΔM_{B_d}	0.507 ± 0.005 ps^{-1}	ΔM_{B_s}	17.77 ± 0.12 p
δa_τ	$< 1.1 \times 10^{-3}$	d_e	$< 1.6 \times 10^{-27}$
d_μ	$< 2.8 \times 10^{-19}$	d_τ	$< 1.1 \times 10^{-17}$
$Br(\mu \to e\gamma)$	$< 2.8 \times 10^{-11}$	$Br(\tau \to e\gamma)$	$< 3.3 \times 10^{-8}$
$Br(\tau \to \mu\gamma)$	$< 4.4 \times 10^{-8}$	$Br(\mu \to 3\,e)$	$< 2.8 \times 10^{-11}$
$Br(\tau \to 3\,e)$	$< 2.0 \times 10^{-10}$	$Br(\tau \to 3\,\mu)$	$< 1.0 \times 10^{-9}$

Table: Summary of observables used from SPHENO.

Phys. Rev. Lett. 109 (2012) 161802.

$$\Delta_{EW} \equiv max_i\,(C_i)\,/(m_Z^2/2). \tag{9}$$

$$\begin{aligned}
C_\mu &= |-\mu^2|,\\
C_{H_u} &= |-m_{H_u}^2 \tan^2\beta/(\tan^2\beta-1)|,\\
C_{H_d} &= |m_{H_d}^2/(\tan^2\beta-1)|,\\
C_{\Sigma_d^d} &= |\Sigma_d^d/(\tan^2\beta-1)|,\\
C_{\Sigma_u^u} &= |-\Sigma_u^u \tan^2\beta/(\tan^2\beta-1)|,\\
\Sigma_{d,u}^{d,u} &= \Sigma_i\,|\Sigma_{d,u}^{d,u}|.
\end{aligned} \tag{10}$$

NPB 306(1988)63, JHEP 0704(2007)070

$$\Delta(\xi) = \left| \frac{\partial \log m_Z^2}{\partial \log \xi} \right| . \tag{11}$$

$$\begin{aligned}
\Delta(\mu) &= \frac{4\mu^2}{m_Z^2}\left(1 + \frac{m_A^2 + m_Z^2}{m_A^2}\tan^2 2\beta\right), \quad \Delta(m_3^2) = \left(1 + \frac{m_A^2}{m_Z^2}\right)\tan^2 2\beta, \\
\Delta(m_{H_1}^2) &= \left|\frac{1}{2}\cos 2\beta + \frac{m_A^2}{m_Z^2}\cos^2\beta - \frac{\mu^2}{m_Z^2}\right| \times \left(1 - \frac{1}{\cos 2\beta} + \frac{m_A^2 + m_Z^2}{m_A^2}\tan^2 \right. \\
\Delta(m_{H_2}^2) &= \left|-\frac{1}{2}\cos 2\beta + \frac{m_A^2}{m_Z^2}\sin^2\beta - \frac{\mu^2}{m_Z^2}\right| \times \left|1 + \frac{1}{\cos 2\beta} + \frac{m_A^2 + m_Z^2}{m_A^2}\tan^2 \right.
\end{aligned}$$

$$\Delta_T \equiv \max(\Delta(\mu),\ \Delta(m_3^2),\ \Delta(m_{H_1}^2),\ \Delta(m_{H_2}^2)). \tag{13}$$