Reconstructing Supersymmetric Theories at High Energy Scales

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Overview:

- *Statement of the problem*
- *Top-down approach*
- *Bottom-up approach*
- *Experimental Errors*
- *Numerical Procedure*
- *Results*
- *Summary*

G.A. Blair, W. Porod, P.M.Zerwas, hep-ph/0007107

Statement of the Problem:

Supersymmetry is broken... how?

mSUGRA*:

- SUSY Breaking mediated via gravitational interactions.
- Gauge Unification at GUT Scale
- Universal input Parameters (at GUT Scale):

$$\mathrm{M}_0,\ \mathrm{M}_{\frac{1}{2}},\ \mathrm{A}_0,\ \tan\beta,\ \mathrm{sign}(\mu)$$

GMSB†:

- SUSY Breaking mediated via gauge interactions.
- Messenger scale M_m
- $\Lambda = \mathrm{F/S}$
- n_5, n_{10}

$$\mathrm{M}_0(M_m, \Lambda, n_i, ...),\ \mathrm{M}_{\frac{1}{2}}(M_m, \Lambda, ...),\ \mathrm{A}_0,\ \tan\beta,\ \mathrm{sign}(\mu)$$

others?

- Gaugino Mediated
- Anomaly Mediated

⋮

* H.P.Nilles, Phys Rep 110, 1 (1984)

† G.F.Guidice and R.Ratazzi, Phys Rep. 322, 419 (1999)

Soft SUSY Breaking Parameters:

Regardless of how SUSY is broken, the result is a set of parameters, P_i, which give rise to soft sparticle mass terms.

- Gaugino Masses: U(1), SU(2), SU(3)

$$M_1\lambda_1\lambda_1 + M_2\lambda_2\lambda_2 + M_3\lambda_3\lambda_3 + h.c.$$

- Scalar Masses:

$$M^2_{Q_{ij}}\tilde{q}^*_{L_j}\tilde{q}_{L_i} + M^2_{U_{ij}}\tilde{u}^*_{R_j}\tilde{u}_{R_i} + M^2_{D_{ij}}\tilde{d}^*_{R_j}\tilde{d}_{R_i} + M^2_{L_{ij}}\tilde{l}^*_{L_j}\tilde{l}_{L_i} +$$
$$M^2_{Eij}\tilde{e}^*_{Rj}\tilde{e}_{R_i} + M^2_{H_1}\tilde{h}^*_1\tilde{h}_1 + M^2_{H_2}\tilde{h}^*_2\tilde{h}_2$$

- Trilinear Couplings:

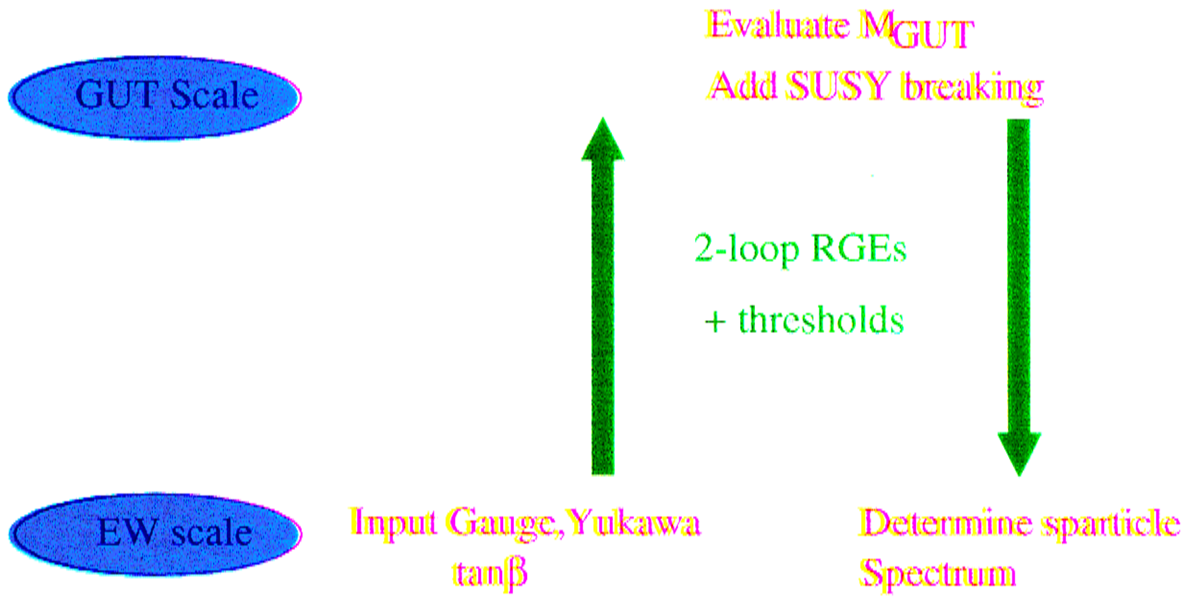
$$\epsilon_{jk}\left(H^j_1(\tilde{e}^*_R a_l \tilde{l}^k_L + \tilde{d}^*_R a_d \tilde{q}^k_L) - H^j_2(\tilde{u}^*_R a_u \tilde{q}^k_L)\right) + h.c.$$

Simplifying Assumptions:

- No complex phases
- No new generation mixing for the sfermions
- No LR mixing for the first two generations.

All the P_i run with the energy scale ...

Setting up the Model:



- First determine M_{GUT} (for mSUGRA - M_m for GMSB) by evolving RGE's upwards.
- At M_{GUT}, input the values of M_0,$M_{\frac{1}{2}}$,A, $\tan\beta$, sign(μ).
- Evolve downwards to determine electroweak sparticle spectrum.
- Assume radiative electroweak symmetry breaking:

$$|\mu|^2 = \frac{m_{H2}^2 \sin^2\beta - m_{H1}^2 \cos^2\beta}{\cos 2\beta} - \frac{1}{2} m_Z^2 + \text{rad.corr.}$$

RGE's: S.Martin and M.Vaughn, Phys. Rev. D50, 2282 (1994); Y.Yamada, Phys.Rev.D50, 3537 (1994); I.Jack and D.R.T.Jones, Phys Lett B333,372 (1994).

Thresholds: J.Bagger, K Matchev, D.Pierce and R.Zhang, Nucl.Phys.B491,3 (1997).

A Very Rich Sparticle Spectrum:

SUSY models will yield many thresholds, each of which provides information on the fundamental parameters.

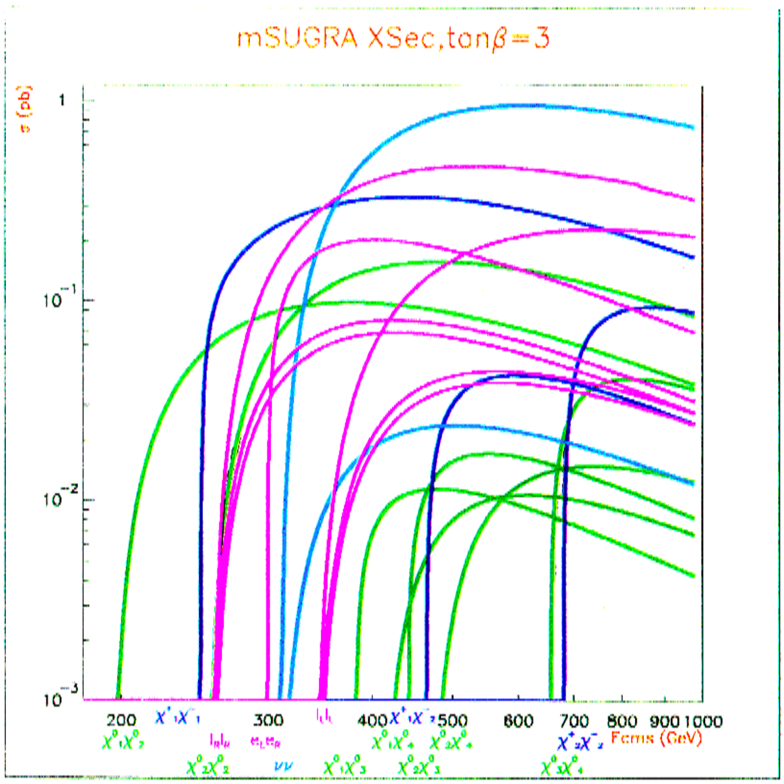


Figure 1: Cross sections for SUSY production for the mSUGRA point
$m_0 = 100$GeV $M_{\frac{1}{2}} = 200$ GeV $A = 0$ GeV sign(μ)=+
RGE performed using separate theoretical algorithms supplied by S Ambrosanio and W Porod, which use 2-loop RGEs for gauge couplings, gaugino masses and 3rd generation Yukawas and one loop for the other soft masses and couplings. The theoretical algorithms were interfaced to SUSYGEN and PYTHIA to obtain physical masses and cross sections.
G A Blair

What is the best way to extract the underlying SUSY model? $\Longrightarrow$ fit to the spectrum.

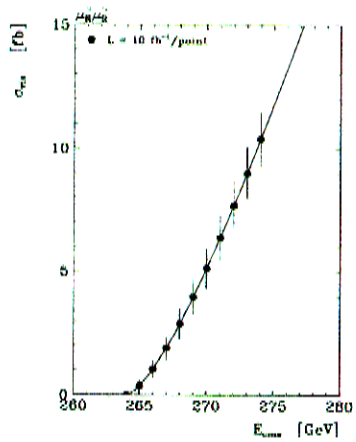
First attach experimental errors to the masses and cross sections...

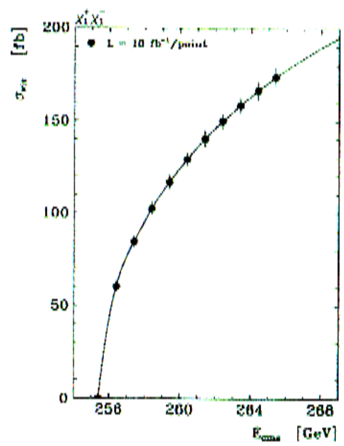
Estimates of Experimental Precisions:

For this study, we restrict ourselves to mass and cross-section measurements.

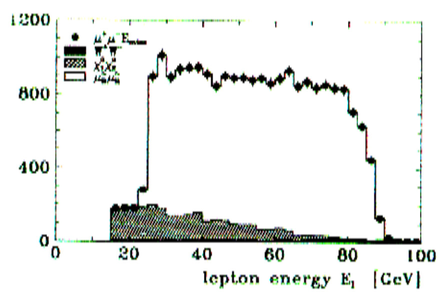
A detailed study exists* for the mass measurements of a low $\tan\beta$ ($=3$) model, assuming 100 fb^{-1} at each ~~point~~. scan.

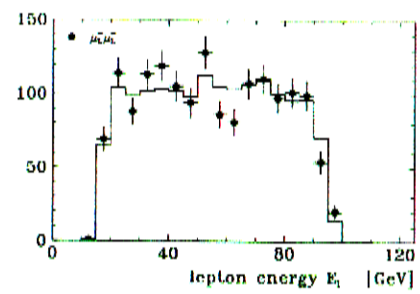
Threshold scans:





Endpoint measurements:





$\Longrightarrow$ typically per mille accuracy on mass determination

$\Longrightarrow$ a strong argument for high luminosity

* U.Martyn et al., hep-ph/9910416

Top-down extraction of parameters:

Assuming a top-down approach, where M_0,$M_{\frac{1}{2}}$,A, $\tan\beta$ are allowed to vary at the GUT Scale assuming mSUGRA led to:

parameter	true value	error
m_0	100 GeV	0.09 GeV
$m_{1/2}$	200 GeV	0.10 GeV
A_0	0 GeV	6.3 GeV
$\tan\beta$	3	0.02
sgn(μ)	$+$	not fit

Allowing M_1 and M_2 to vary independently leads to:

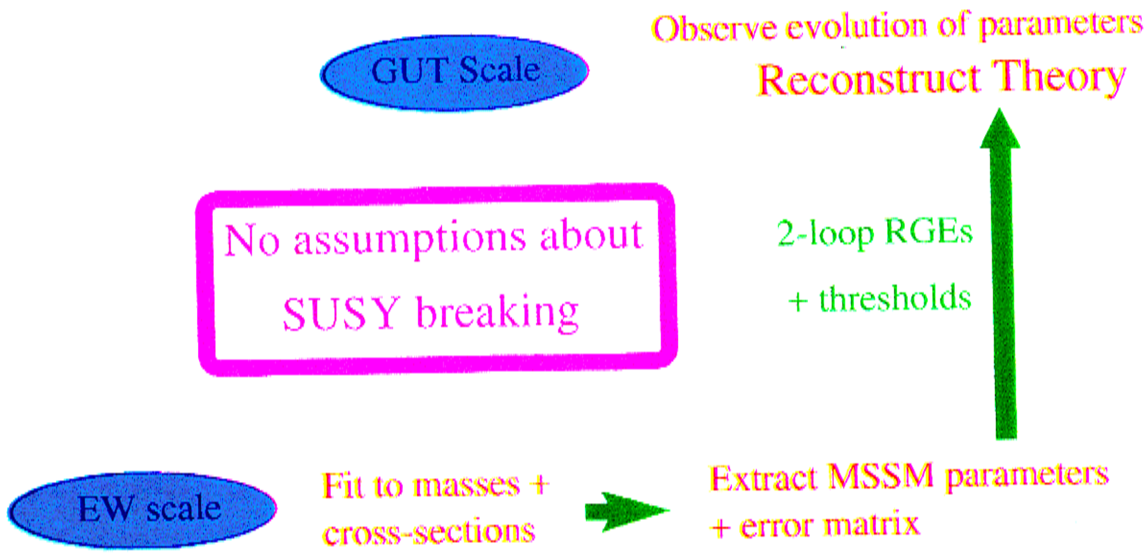
parameter	true value	error
m_0	100 GeV	0.09 GeV
M_1	200 GeV	0.20 GeV
M_2	200 GeV	0.20 GeV
A_0	0 GeV	10.3 GeV
$\tan\beta$	3	0.04
sgn(μ)	$+$	not fit

Conclusion: the top-down approach, combined with LC errors, gives excellent mSUGRA parameter determination.

BUT: the model assumption could hide the true structure ...

So: Adopt a bottom-up approach:

Bottom-up approach:



- Fit to the mass spectrum + cross-sections at EW scale.
- Use conservative estimates for errors (see below).
- Extract MSSM parameters + error matrix at EW scale

EW scale parameters: $M_{E_k}, M_{L_k}, M_{D_k}, M_{Q_k}, M_{U_k}, A_\tau, A_b, A_t,$ M_{H_1}, M_{H_2}, M_i, $\tan\beta$, k=1,3, $i = 1, 2, 3$

Finally

- Input measured particle spectrum into RGE's.
- Evolve RGE's upwards.
- Importantly: reconstruct theory, without bias.

Additional Comments on the Approaches:

- The Bottom-Up approach manifests the quality of the reconstruction in a more transparent form.
- The search for regularity at the GUT scale may reveal irregularity.
- If new intermediate scales are present between the electroweak scale and the fundamental high-energy scale $\Longrightarrow$ evolution equations would have to be adjusted accordingly.
- However, new scales may become apparent in the bottom-up approach (see GMSB below).
- Top-down approaches may give misleadingly good agreement because theories with pseudo-fixed point structure run into quite similar effective low-energy theories.
- High accuracy will be needed for the extrapolations if the universality at the GUT scale is only slightly broken.

Large tanβ Model:

The mSUGRA model we use in the following is:

$\tan\beta = 30$, M_0=200 GeV, $M_{\frac{1}{2}}$=190 GeV, A_0=550 GeV, sign(μ)=-1.

The GMSB model we assume is:

$\tan\beta = 30$, $M_m = 2 \times 10^5$ TeV, Λ =28 TeV, N_5 =3, $A_0 = 0$, sign(μ)=-1.

- Compatible with LEP higgs SUSY limits (?).
- Compatible with $b \to s\gamma$.
- Compatible with ρ parameter.

Important new phenomenology from large tanβ: multi τ final states.

Modifications with respect to the previous low tan beta analysis:

$\Longrightarrow$ conservative τ event reconstruction efficiency $\epsilon = 20\%$. †
($\Delta\sigma = \sqrt{\frac{\sigma}{\mathcal{L}\epsilon}}$)

$\Longrightarrow$ Errors on masses for particles that decay predominantly to τ final states are inflated by a factor of $\sim$3 .

$\Longrightarrow$ Errors are scaled according to the new nominal particle masses.

Squark mass measurements require

- $\sqrt{s} = 1$ TeV for our mSUGRA model.
- $\sqrt{s} = 1.5$ TeV for our GMSB model.

† see eg M.M.Nojiri,K.Fujii, and T.Tsukamoto, Phys.Rev.D54,6756 (1996)

Assumptions Used in Fits:

- $\mathcal{L}$= 100 fb^{-1} for each scanned point
- $\mathcal{L}$= 500 fb^{-1} for each polarized cross-section measurement.
- Polarization: e^-:80%, e^+:60%.
- No colour- (or charge-) breaking minima are allowed as solutions in fit.
- Representative LHC errors† assumed for more massive sparticles

mSUGRA model

Particle	M(GeV)	Δ M(GeV)	
	Mass	LHC	LHC+LC
h^0	109	0.2	0.05
A^0	191	3	1.5
χ_1^+	133	3	0.11
χ_1^0	72.6	3	0.15
$\tilde{\nu}_e$	233	3	0.1
$\tilde{e}_1$	217	3	0.15
$\tilde{\nu}_\tau$	214	3	0.8
$\tilde{\tau}_1$	154	3	0.7
$\tilde{u}_1$	466	10	1
$\tilde{t}_1$	377	10	1
$\tilde{g}$	470	10	10

† ATLAS TDR, CERN/LHCC/99-15.

mSUGRA Fit Results:

	LHC +Linear Collider	
	exp. input	GUT value
M_1	75.59 ± 0.16	189.6 ± 0.66
M_2	143.62 ± 0.16	189.4 ± 0.76
M_3	452.3 ± 8	189.7 ± 3.7
M_{L_1}	236.76 ± 0.13	200.3 ± 0.62
M_{Q_1}	459.66 ± 0.53	202 ± 15
M_{L_3}	218.61 ± 0.64	196 ± 6.1
M_{Q_3}	391.96 ± 0.90	221 ± 33
M_{H_1}	132.4 ± 1.5	226 ± 76
$\|M_{H_2}\|$	-251.9 ± 0.18	206 ± 22
A_τ	100 ± 88	318 ± 310
A_b	-126 ± 237	212 ± 446
A_t	-186.3 ± 2.3	504 ± 69

EW scale $\rightarrow$ GUT scale

- (-) refers to negative value of $M_{H_2}^2$ at EW scale
- Errors correspond to 1 σ
- Model: $\tan\beta = 30$, M_0=200 GeV, $M_{\frac{1}{2}}$=190 GeV, A_0=550 GeV, sign(μ)=-1.

SUGRA with LHC only errors

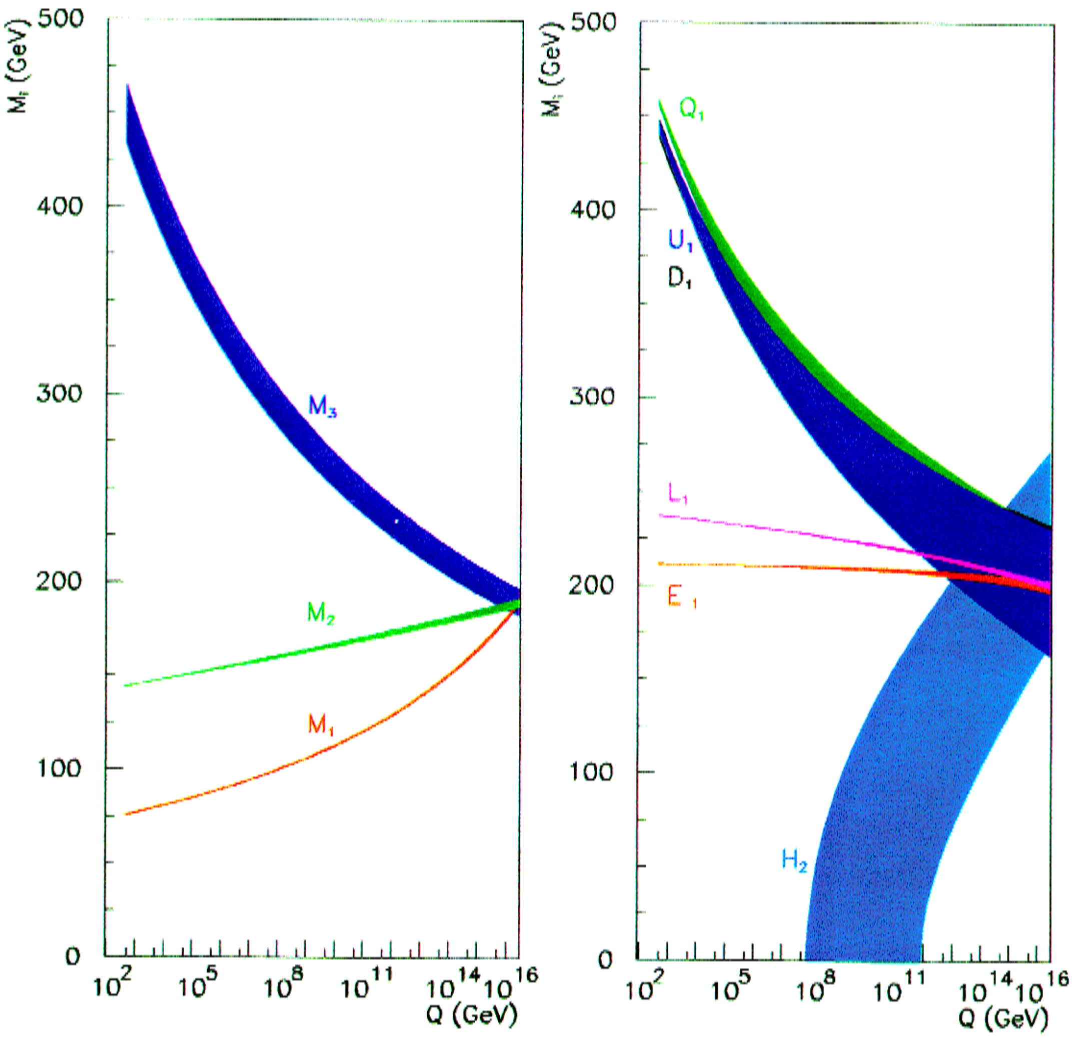
	LHC Only	
	exp. input	GUT value
M_1	75.6 ± 3.2	189.6 ± 7.6
M_2	143.6 ± 3.1	190.6 ± 3.8
M_3	452.3 ± 11.9	190.1 ± 5.7
M_{L_1}	236.8 ± 2.1	200.6 ± 6.9
M_{Q_1}	459.6 ± 7.4	200.7 ± 30.5
M_{L_3}	218.6± 2.8	199.5 ± 12.3
M_{Q_3}	392 ± 45	192 ± 251
M_{H_1}	132.4 ±12	361 ± 324
$\|M_{H_2}\|$	-251.9 ±2.2	279 ± 98
A_τ	101 ± 2590	210 ± 432
A_b	-125 ± 3920	806 ± 1292
A_t	-186 ± 39	608 ± 169

EW scale → GUT scale

- Errors only representative - a full analysis has not been carried out at the LHC for this model.
- LHC data clearly can benefit from LC input.

mSUGRA

$\tan\beta = 30$, M_0=200 GeV, $M_{\frac{1}{2}}$=190 GeV, A_0=550 GeV, sign(μ)=-1

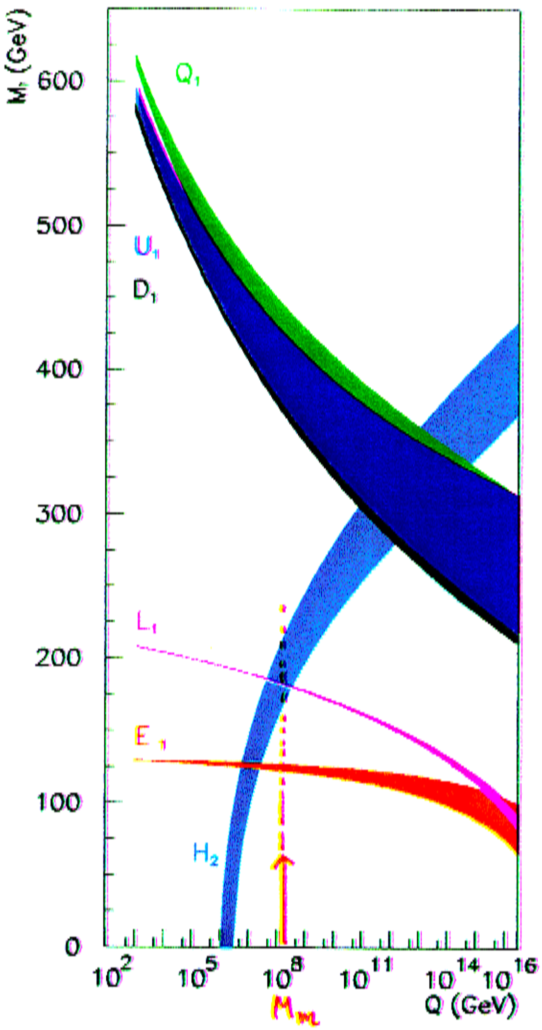


The widths of the bands indicate the 95% CL.

- Slepton sector is under very good control
- M_3 accuracy limited by the gluino mass precision.
- Unification of parameters is reconstructed.

GMSB

$\tan\beta = 30$, $M_m = 2\times10^5$ TeV, Λ =28 TeV, N_5 =3, $A_0 = 0$, sign(μ)=-1.

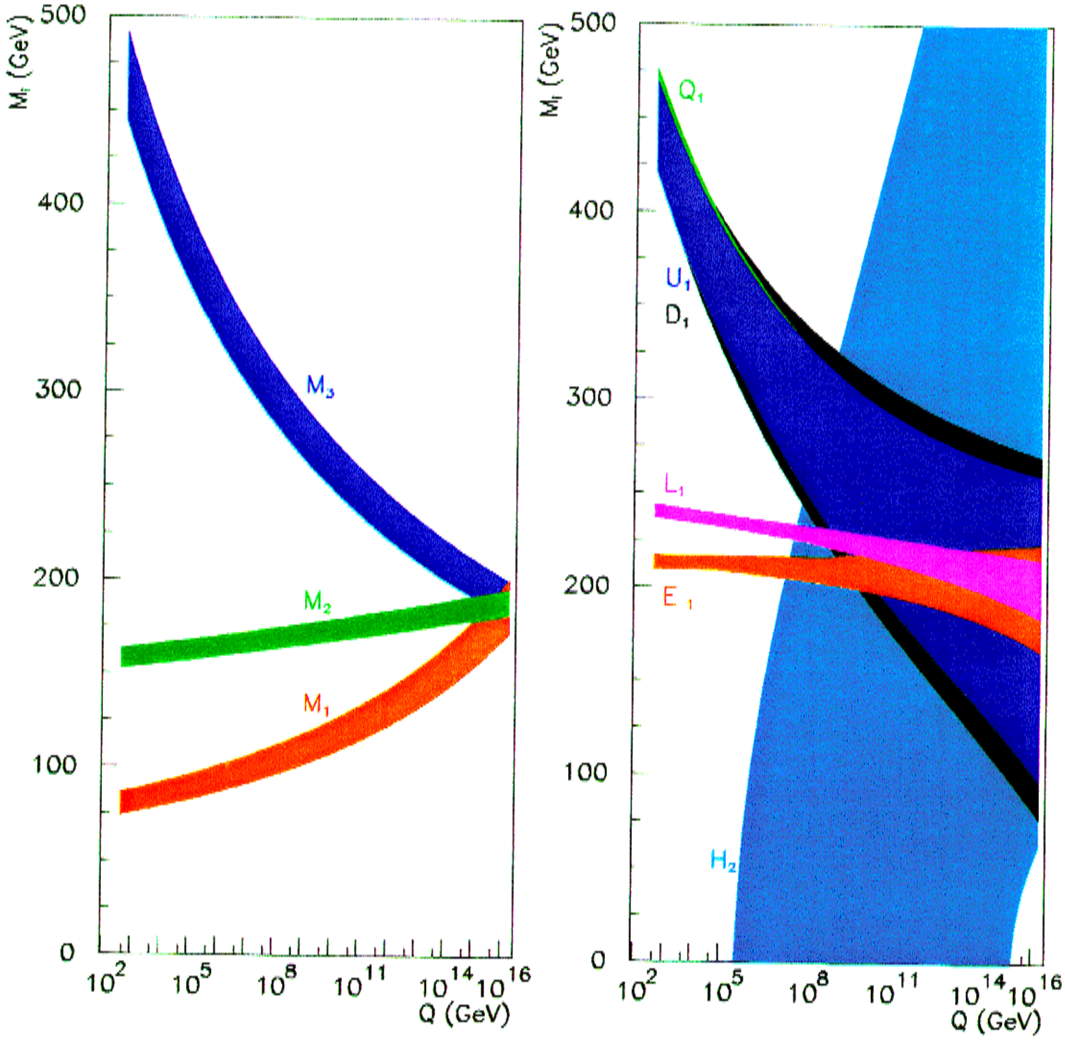


The widths of the bands indicate the 95% CL.

- No confusion with mSUGRA.
- Reconstruction of Unification of $M^2_{L_1}$ and $M^2_{H_2}$ at M_m.

SUGRA with LHC only errors

$\tan\beta = 30$, M_0=200 GeV, $M_{\frac{1}{2}}$=190 GeV, A_0=550 GeV, sign(μ)=-1

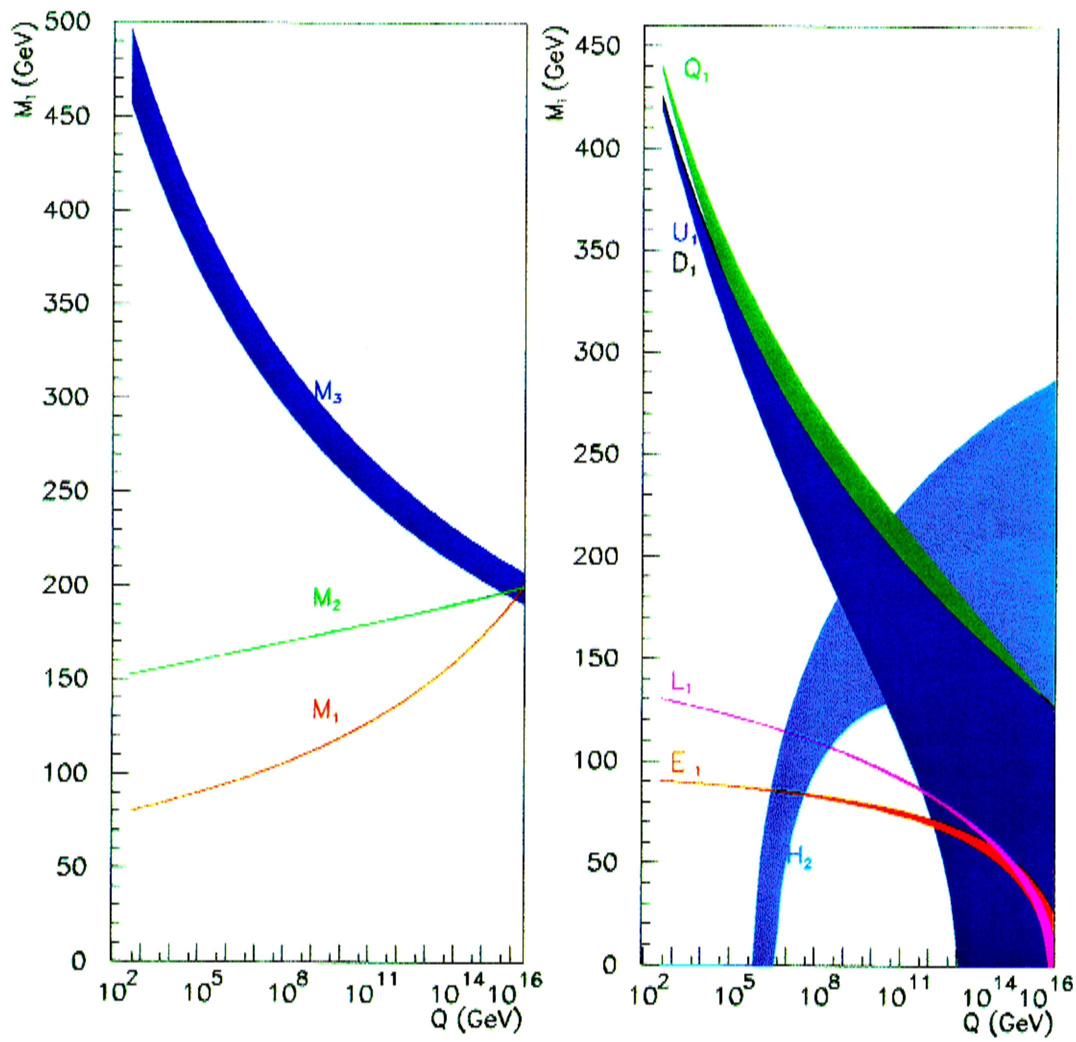


The widths of the bands indicate the 95% CL.

- Assumption of unification is less secure.
- Top-down approach may lead to incomplete picture.

A Gaugino-Mediated Model

$\tan\beta = 2.5$, M_0=5 GeV, $M_{\frac{1}{2}}$=200 GeV, A_0=0 GeV,
$M_{H_1} = 300$GeV, $M_{H_2} = 200$GeV, sign(μ)=-1†



- Higher efficiency (80%) used for cross-section measurements.
- Experimental errors increased for sneutrinos (invisible decays).

† Z.Chacko, M.A.Luty, A.E.Nelson,E.Ponton hep-ph/9911323

SUMMARY

- A bottom-up approach allows the theory to be reconstructed in an unbiased way.
- Assuming no new intermediate mass scales, the RGE's are specified by the low-energy spectrum.
- New patterns of unification at intermediate scales may be made evident by this approach, in a model-independent way.
- This has been shown by a range of examples.
- The accuracy of the approach is significantly improved by adding LC data to that of the LHC.

Special thanks to my collaborators: W Porod, U Martyn, P Zerwas.