General Gauge Mediation and Renormalization Group Invariants in the Minimal Supersymmetric Standard Model

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M. Carena, P. Draper, N. R. Shah and C. Wagner [arXiv:1005.SOON[hep-ph]].

Outline

- Introduction.
- MSSM .
- 1-Loop RG Invariants constructed.
- 1-Loop RG Invariants used to test large class of models in which SUSY breaking is flavor blind.
- 2-Loop effects on invariants analyzed and always included.
- Example of power of RGIs, consider sub-class of theories: GGM.
- Numerical simulation: scan over model space of GGM,
  - Demonstrate that certain invariants may be used to test GGM hypothesis.
  - If data consistent with model, RGIs may be used to extract information about soft SUSY breaking parameters.
  - Demonstrate expected determination of parameters depending on experimental errors at LHC in measuring the physical sparticle masses.
- Outlook and Conclusions.

- Assumptions:
  - Effective theory at electroweak scale is MSSM.
  - No new physics alters 1-loop MSSM β functions below messenger scale, at which SUSY breaking is transmitted to visible sector.
- MSSM:
  - Particle content governed by SUSY, and couplings by SM gauge and Yukawa couplings.
  - Soft SUSY breaking parameters governing sparticle masses unknown.
    - Highly dependent on SUSY breaking scheme.
  - If sparticles light, flavor physics strongly constrains structure of soft masses.
- GGM:
  - Naturally fulfills flavor constraints.
  - Mass spectrum at LHC energies much more complicated than in more minimal models.

Could LHC measurements determine :

Messenger scale?

Soft SUSY breaking parameters ?

- TOOL:
  - 1-Loop RG Invariants in the MSSM.
    - Do 2-loop effects spoil invariance?
    - Effect on extraction of high scale parameters?
    - Experimental constraints need to be satisfied to extract information?

The Minimal Supersymmetric Standard Model.

Particle Content

Names		spin 0	spin 1/2	$SU(3)_C, SU(2)_L, U(1)_Y$
squarks, quarks	Q	$(\widetilde{u}_L \ \ \widetilde{d}_L)$	$(u_L \ \ d_L)$	$(\mathbf{3}, \mathbf{2}, \frac{1}{6})$
(×3 families)	$\overline{u}$	$\widetilde{u}^*_R$	$u^\dagger_R$	$(\overline{\mathbf{3}}, \mathbf{1}, -\frac{2}{3})$
	$\overline{d}$	$\widetilde{d}^*_R$	$d^\dagger_R$	$(\overline{\mathbf{3}}, \mathbf{1}, \frac{1}{3})$
sleptons, leptons	L	$(\widetilde{\nu} \ \widetilde{e}_L)$	$(\nu \ \ e_L)$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$
(×3 families)	$\overline{e}$	$\widetilde{e}^*_R$	$e^\dagger_R$	$(\mathbf{1}, \mathbf{1}, 1)$
Higgs, higgsinos	H_u	$(H_u^+ \ \ H_u^0)$	$(\widetilde{H}_u^+ \ \ \widetilde{H}_u^0)$	$(\mathbf{1}, \mathbf{2}, +\frac{1}{2})$
	H_d	$(H_d^0 \ \ H_d^-)$	$(\widetilde{H}_d^0 \ \ \widetilde{H}_d^-)$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$

- Chiral supermultiplets in MSSM:
  - Spin-0 fields are complex scalars,
  - Spin-1/2 fields are left-handed two-component Weyl fermions.

Names	spin 1/2	spin 1	$SU(3)_C, SU(2)_L, U(1)_Y$
gluino, gluon	$\widetilde{g}$	g	$(\mathbf{8}, \mathbf{1}, 0)$
winos, W bosons	$\widetilde{W}^\pm \ \ \widetilde{W}^0$	$W^\pm \ \ W^0$	$(\mathbf{1}, \mathbf{3}, 0)$
bino, B boson	$\widetilde{B}^0$	B^0	$(\mathbf{1}, \mathbf{1}, 0)$

- Gauge supermultiplets in the MSSM.

Table 1: U(1) Representations in the MSSM

Particle	Y	B	L
$Q=\begin{pmatrix} u \\ d \end{pmatrix}_L$	1/6	1/3	0
$L=\begin{pmatrix} \nu \\ l \end{pmatrix}_L$	-1/2	0	1
$u=u_R^C$	-2/3	-1/3	0
$d=d_R^C$	1/3	-1/3	0
$e=l_R^C$	1	0	-1
H_u	1/2	0	0
H_d	-1/2	0	0

1-Loop RG Evolution

- Assume
  - soft sfermion masses flavor diagonal.
  - 1st and 2nd generation masses degenerate at the messenger scale.
  - Neglect 1st and 2nd generation yukawa and trilinear couplings.

$$16\pi^2 \frac{dm_i^2}{dt} = \sum_{jk} y_{ijk}^* y^{ijk}(m_i^2 + m_j^2 + m_k^2 + A_{ijk}^* A^{ijk}) - 8\sum_a C_a(i) g_a^2 |M_a|^2 + \frac{6}{5} Y_i g_a^2 D_Y \, ,$$

  - First sum: degrees of freedom available to run in self-energy loop.
  - Second sum: gauge groups.
  - C is quadratic Casimir.
  - Trace in D_Y : all chiral multiplets.

$$D_Y \equiv \mathrm{Tr}_i(Y_i m_i^2) = \sum_{gen} \left(m_{\tilde{Q}}^2 - 2m_{\tilde{u}}^2 + m_{\tilde{d}}^2 - m_{\tilde{L}}^2 + m_{\tilde{e}}^2\right) + m_{H_u}^2 - m_{H_d}^2 .$$

- Gauge couplings: homogenous RGEs at 1-loop:

$$16\pi^2 \frac{dg_r}{dt} = g_r^3 \left(\mathrm{Tr}_n \, I_r(n) - 3C_r(G)\right) ,$$

  - Here C is the quadratic Casimir of the adjoint representation.
- Three soft gaugino masses evolve: $16\pi^2 \partial_t M_r = g_r^2 M_r \left(2\,\mathrm{Tr}_n \, I_r(n) - 6C_r(G)\right) .$

Constructing 1-Loop Renormalization Group Invariants

Sfermion dependant Invariants.

- Construct linear combinations of soft masses, D_i, evolving only with D_Y

$$D_i \equiv \sum_j Q_j m_j^2, \qquad \frac{dD_i}{dt} = a_i D_y,$$

- Six combinations:
  - For yukawa terms to vanish,
    - Q_is must correspond to charges of global symmetry of classical yukawa potential.
      - Implies three independent constraints on the 12 Q_is.
  - For gaugino terms to cancel,
    - Symmetry must have vanishing mixed anomalies with SM gauge groups.
      - Supplies three more independent constraints on the Q_is.
- Can construct basis in which 5 of 6 combinations also satisfy TrQY=0,
  - Cancels D_Y dependence.
  - Promotes them to 1-loop RG Invariants, independent of vanishing of D_Y.

Invariants Testing Flavor Structure

- Baryon Number (Q=B) and Lepton Number (Q=L)
  - Classical symmetries, anomalous in the MSSM.
  - Our approximation: B and L anomalies flavor independent.
  - Difference between the first (second) and third generation is anomaly free.
- We can then generate two invariants:

$$D_{L_{13}} \equiv D_{L_1} - D_{L_3}$$

$$D_{B_{13}} \equiv D_{B_1} - D_{B_3}$$

Anomalous U(1)s and Invariants involving Gauge Couplings/Gaugino Masses

- Obvious choice: *Y* and (*B*-*L*):
  - Evolve with D_Y.
- Use similar idea for *Y* as with *B* and *L*.
  - Must include Higgs doublet with 3rd generation, since evolution linked with yukawas.
- The RG Invariant is given by:

$$D_{Y_{13H}} \equiv D_{Y_1} - \frac{10}{13} D_{Y_{3H}}$$

- For (*B*-*L*), generation subtraction redundant: can already be constructed out of *B13* and *L13*.
- Restricted to one generation, D_Y and $D_{(B\text{-}L)}$ evolve only with D_Y
  - Construct RGI depending only on 1st generation soft masses:

$$D_{\chi 1} \equiv 4D_{Y_1} - 5D_{(B-L)_1}$$

  - Identified with $U(1)_\Xi$ generated in breaking of E_6 to $SU(5) \times U(1)_\Xi \times U(1)$.
- Anomalous combination of both U(1)s, setting 1st generation left handed slepton charges to zero: obtain additional anomaly free $U(1)_Z$:

$$D_Z \equiv 3m^2_{\tilde{d}_3} + 2m^2_{\tilde{L}_3} - 2m^2_{H_d} - 3m^2_{\tilde{d}_1}.$$

- D_Y vanishes only in minimal GGM.
  - Construct genuine invariant using the RGE for g_1:

$$I_{Y\alpha} \equiv \frac{D_Y}{g_1^2}.$$

- From RGEs for gauge couplings, we can further obtain:

$$I_{g_2} \equiv \frac{1}{g_1^2} - \frac{33}{5g_2^2} \qquad I_{g_3} \equiv \frac{1}{g_1^2} + \frac{33}{15g_3^2},$$

- From RGEs for gaugino masse, can construct:

$$I_{B_r} \equiv M_r/g_r^2.$$

- 3 invariants mixing sfermion and gaugino masses can be obtained from the 1st generation:

$$\begin{aligned}
I_{M_1} &\equiv M_1^2 - \frac{33}{8}(m^2_{\tilde{d}_1} - m^2_{\tilde{e}_1} - m^2_{\tilde{u}_1}) \\
I_{M_2} &\equiv M_2^2 - \frac{1}{24}(-9m^2_{\tilde{d}_1} - 16m^2_{\tilde{L}_1} + m^2_{\tilde{e}_1} + 9m^2_{\tilde{u}_1}) \\
I_{M_3} &\equiv M_3^2 - \frac{3}{16}(5m^2_{\tilde{d}_1} - m^2_{\tilde{e}_1} + m^2_{\tilde{u}_1}).
\end{aligned}$$

2-Loop Effects?

- All RGIs defined so far have vanishing β-functions only at 1-loop level.
- Can easily check invariance not preserved at 2-loops.
  - Important to estimate 2-loop effects.
  - How do they compare to expected experimental errors in measurements of invariants?
  - How does this constrain experimental accuracy required to determine any high scale model parameters?
- Implemented full 2-loop RGEs for evolution of soft SUSY breaking parameters, gauge and Yukawa couplings when performing numerical simulations in Mathematica.
- Compared our mass spectrum to one obtained from SUSPECT and obtained excellent agreement.

General Gauge Mediation

Soft SUSY Breaking Masses

- GGM provides class of models in which perhaps flavor blindness is most natural.

At the Messenger Scale

- Soft sfermion masses are parameterized in terms of three numbers A_r originating from hidden sector current-current correlation functions.

$$m_{\tilde{f}}^2 = g_1^2 Y_{\tilde{f}} \xi + \sum_{r=1}^{3} g_r^4 C_r(f) A_r$$

- Assume Fayet Iliopoulos term is zero.
- Gaugino masses given in terms of three more numbers B_r:

$$M_r = g_r^2 M B_r,$$

- To generate Higgsino mass parameter, μ, may need supplemental SUSY breaking in the Higgs sector, modifying Higgs mass parameters:

$$m_{H_u}^2 = m_{\tilde{L}_3}^2 + \delta_u$$
$$m_{H_d}^2 = m_{\tilde{L}_3}^2 + \delta_d.$$

Invariant	Symmetry	Expression	GGM Value
$D_{B_{13}}$	$B_1 - B_3$	$2m^2_{\tilde{Q}_1} - m^2_{\tilde{u}_1} - m^2_{\tilde{d}_1} - 2m^2_{\tilde{Q}_3} + m^2_{\tilde{u}_3} + m^2_{\tilde{d}_3}$	0
$D_{L_{13}}$	$L_1 - L_3$	$2m^2_{\tilde{L}_1} - m^2_{\tilde{e}_1} - 2m^2_{\tilde{L}_3} + m^2_{\tilde{e}_3}$	0
D_{χ_1}	χ_1	$-6m^2_{\tilde{Q}_1} - 3m^2_{\tilde{u}_1} + 9m^2_{\tilde{d}_1} + 6m^2_{\tilde{L}_1} - m^2_{\tilde{e}_1}$	0
$D_{Y_{13H}}$	$Y_1 - \frac{10}{13}Y_{3H}$	$m^2_{\tilde{Q}_1} - 2m^2_{\tilde{u}_1} + m^2_{\tilde{d}_1} - m^2_{\tilde{L}_1} + m^2_{\tilde{e}_1}$ $-\frac{10}{13}\left(m^2_{\tilde{Q}_3} - 2m^2_{\tilde{u}_3} + m^2_{\tilde{d}_3} - m^2_{\tilde{L}_3} + m^2_{\tilde{e}_3}\right)$ $-\frac{10}{13}\left(m^2_{H_u} - m^2_{H_d}\right)$	$-\frac{10}{13}(\delta_u - \delta_d)$
D_Z	Z	$3m^2_{\tilde{d}_3} + 2m^2_{\tilde{L}_3} - 2m^2_{H_d} - 3m^2_{\tilde{d}_1}$	$-2\delta_d$
$I_{Y\alpha}$	Y	$\frac{\sum_{gen}\left(m^2_{\tilde{Q}} - 2m^2_{\tilde{u}} + m^2_{\tilde{d}} - m^2_{\tilde{L}} + m^2_{\tilde{e}}\right) + m^2_{H_u} - m^2_{H_d}}{g_1^2}$	$\frac{\delta_u - \delta_d}{g_1^2}$
I_{B_r}		$\frac{M_r}{g_r^2}$	MB_r
I_{M_1}		$M_1^2 - \frac{33}{8}(m^2_{\tilde{d}_1} - m^2_{\tilde{e}_1} - m^2_{\tilde{u}_1})$	$g_1^4\left(\frac{33}{10}A_1 + (MB_1)^2\right)$
I_{M_2}		$M_2^2 - \frac{1}{24}(-9m^2_{\tilde{d}_1} - 16m^2_{\tilde{L}_1} + m^2_{\tilde{e}_1} + 9m^2_{\tilde{u}_1})$	$g_2^4\left(\frac{1}{2}A_2 + (MB_2)^2\right)$
I_{M_3}		$M_3^2 - \frac{3}{16}(5m^2_{\tilde{d}_1} - m^2_{\tilde{e}_1} + m^2_{\tilde{u}_1})$	$g_3^4\left((MB_3)^2 - \frac{3}{2}A_3\right)$

$$\delta_u = -\frac{1}{2}D_Z - \frac{13}{10}D_{Y_{13H}}$$
$$\delta_d = -\frac{1}{2}D_Z.$$

$$MB_r = I_{B_r}.$$

$$A_1 = \frac{10}{33}\left(\frac{I_{M_1}}{g_1^4} - I^2_{B_1}\right)$$
$$A_2 = 2\left(\frac{I_{M_2}}{g_2^4} - I^2_{B_2}\right)$$
$$A_3 = \frac{2}{3}\left(\frac{-I_{M_3}}{g_3^4} + I^2_{B_3}\right)$$

If $I_{Y\alpha}$ and $D_{Y_{13H}}$ non-zero, from their ratio we can extract value of g_1, at the high scale, μ_f.

Hence, using the running of g_1, one could determine μ_f .

When errors in the determination of A_r large, can still determine certain correlations between the A_r and g_r with high accuracy:

$$g_1^4\frac{33}{10}A_1 + g_2^4\frac{11}{2}A_2 = I_{M_{12}} - g_1^4 I^2_{B_1} - 11g_2^4 I^2_{B_2}$$

Numerical Simulations and Results.

Procedure

- Scan messenger scale parameter space of models for GGM.
  - A_r: 0.1, 0.55, 1 $(\text{TeV})^2$
  - B_r: 0.1, 0.55, 1 (TeV)
  - δ_u: 0, 0.5, 1 $(\text{TeV})^2$
  - δ_d: 0, 0.5, 1 $(\text{TeV})^2$
  - $\text{Log}[\mu_f/m_Z]$: 12, 21, 30
  - $\text{Tan}(\beta)$: 2, 9, 16
- Compute invariants, soft masses and gauge/yukawa couplings at messenger scale.
- Using 2-loop RGEs, run down to TeV scale.
- Compute invariants, soft masses and physical masses at TeV scale.
- Assume each point in model space maybe an experimental measurement for the soft masses at TeV scale, with error of 1%:
  - Test hypothesis of flavor blindness using first 2 invariants.
  - Test GGM using 3rd Invariant
  - Extract messenger scale parameters from the rest.
- Considered flat 1% experimental error in measurement of all soft masses at TeV scale.
  - Probably highly optimistic
  - In reality would be highly dependant on exact decays chains depending on mass hierarchy, etc used to measure masses experimentally.
  - Since we assume flat % errors, easy to see from plots what change in % error would imply.

Example LHC Accuracy

basic par.	2-loop RGE +full R.C.	1-loop RGE +approx. R.C.	relevant pole masses	2-loop RGE +full R.C.	1-loop RGE +approx. R.C.
Q_{EWSB}	465.5	468.2			
M_1	101.5	108.8	$m_{\tilde{N}_1}$	97.2	105.1
M_2	191.6	208.9	$m_{\tilde{N}_2}$	180.8	189.9
M_3	586.6	603.8	$m_{\tilde{g}}$	606.1	603.8
μ	356.9	340.6	$m_{\tilde{N}_4}$	381.8	369.6
$\tan\beta$	9.74	9.75			
$m^2_{H_d}$	$(179.9)^2$	$(187.3)^2$	m_h	110.85	111.28
$m^2_{H_u}$	$-(358.1)^2$	$-(341.7)^2$			
m_{e_L}	195.5	201.5			
m_{τ_L}	194.7	200.6			
m_{e_R}	136	138.6	$m_{\tilde{e}_2}$	142.8	145.4
m_{τ_R}	133.5	136.2			
$m_{Q_L 1,2}$	545.8	554.1	$m_{\tilde{u}_1}$	562.3	551.6
$m_{Q_L 3}$	497	502.9	$m_{\tilde{b}_1}$	516.2	502.1
m_{u_R}	527.8	531.6			
m_{t_R}	421.5	421.6			
m_{d_R}	525.7	528.7			
m_{b_R}	522.4	525.4	$m_{\tilde{b}_2}$	546.3	530.1
$-A_t$	494.5	501.0			
$-A_b$	795.2	791.3			
$-A_\tau$	251.7	255.0			
$-A_u$	677.3	686.6			
$-A_d$	859.4	857.2			
$-A_e$	253.4	256.7			

Soft and other basic parameters, plus sparticle pole masses for SPS1a input (with m_{top} = 175 GeV), calculated with SuSpect ver 2.41, for two illustrative optional choices:

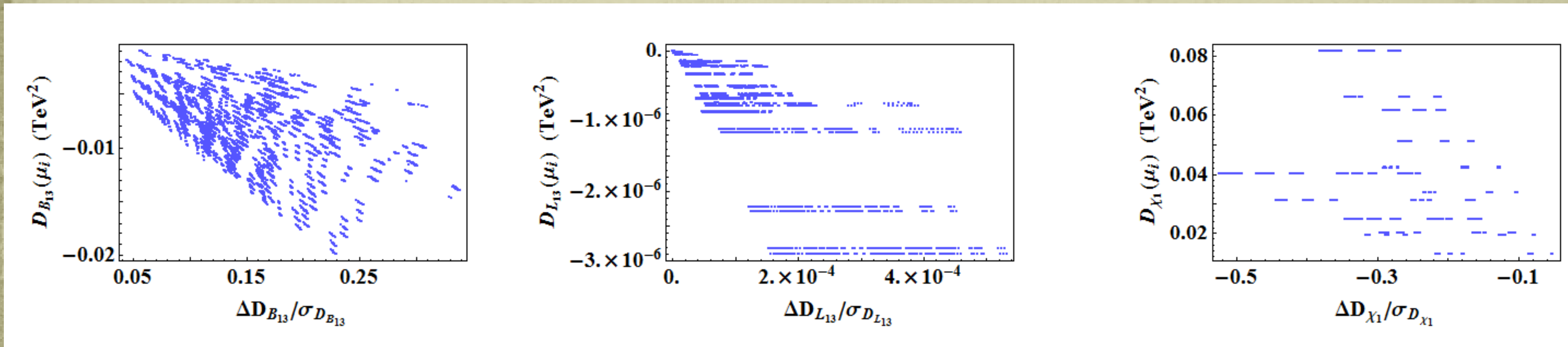
- full two-loop in RGE and full radiative corrections to sparticle masses (second and fifth columns);
- one-loop RGE, no radiative corrections to squarks, gluino, neutralinos, charginos masses, simple approximation for m_h radiative corrections (third and sixth columns).

Experimental accuracies on mass determinations from LHC gluino cascade and other decays.

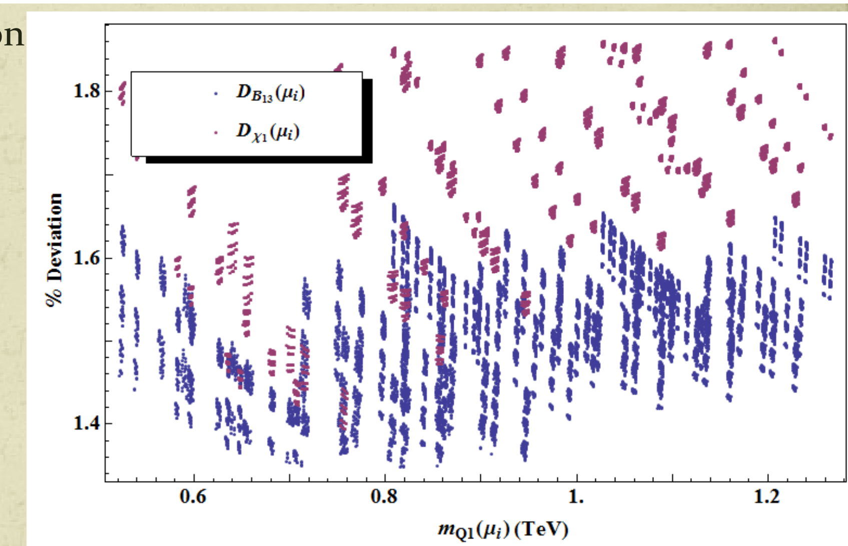
mass	expected LHC accuracy (GeV)	decay or process
$m_{\tilde{g}}$	7.2	$\tilde{g}$ cascade decay
$m_{\tilde{N}_1}$	3.7	" "
$m_{\tilde{N}_2}$	3.6	" "
$m_{\tilde{q}_L}$	3.7	" "
$m_{\tilde{l}_R}$	6.0	" "
$m_{\tilde{N}_4}$	5.1	$\tilde{q}_L \to \tilde{\chi}^0_4 + ..$ cascade
$m_{\tilde{b}_1}$	7.5	$\tilde{g}$ cascade decay
$m_{\tilde{b}_2}$	7.9	" "
m_h	0.25 (exp)–2 (th)	$h \to \gamma\gamma$ (mainly)

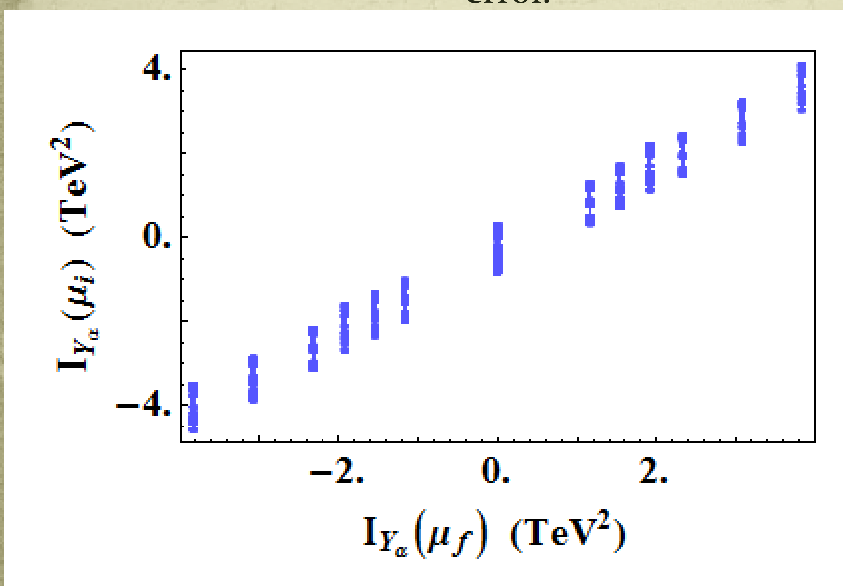
J.-L. Kneur, N. Sahoury, Phys.Rev.D79:075010,2009.
B.Allanach, C.Lester, M.Parker and B.Webber, JHEP 0009 (2000) 004.
G. Weiglein et al, Phys. Rept. 426 (2006) 47.

$\sigma_{\text{soft mass}} = 1\%$: 2-loop Running Preserves Invariance within Error.



Invariants expected to be zero in GGM plotted above as function of ratio of 2-loop running and expected experimental errors. Can invert relationship to extract % deviation in soft masses that could be detected when any of them are non-zero within error.

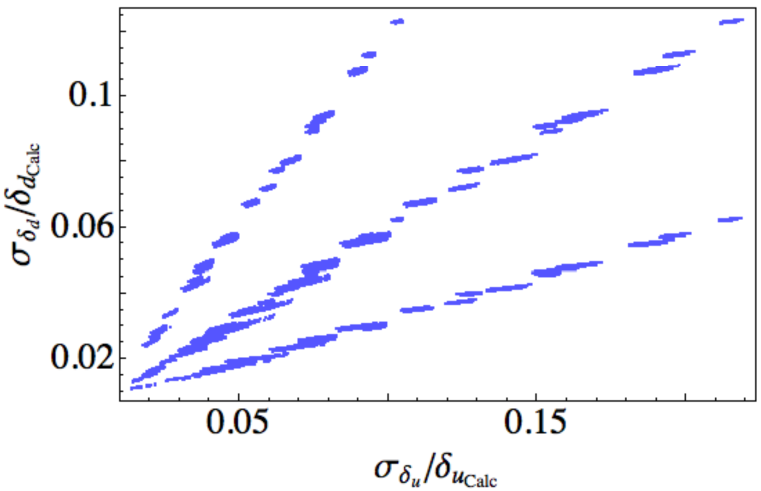


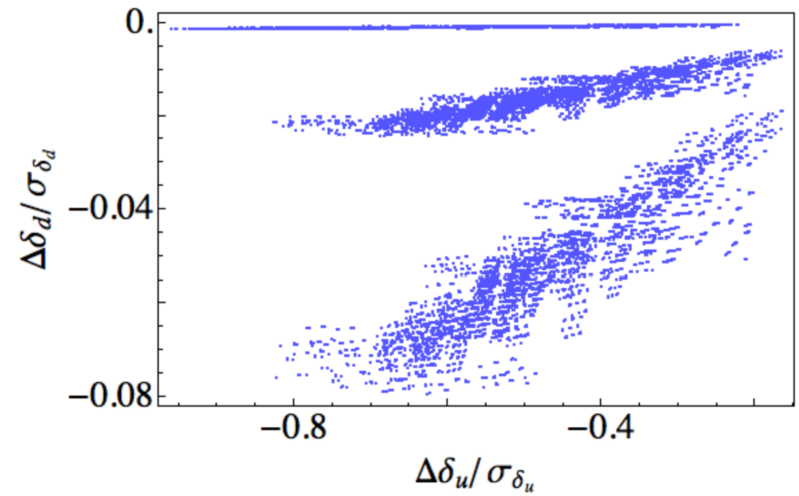


Invariants plotted at high scale vs. low scale with expected error bars. These invariants used as tool to extract high scale parameters from TeV scale measurements.

The GGM parameters B_r can be extracted directly from the invariants with very high accuracy (~2%, with a soft mass error of 1%).

Corrections to the Higgs mass parameters and their expected experimental determination





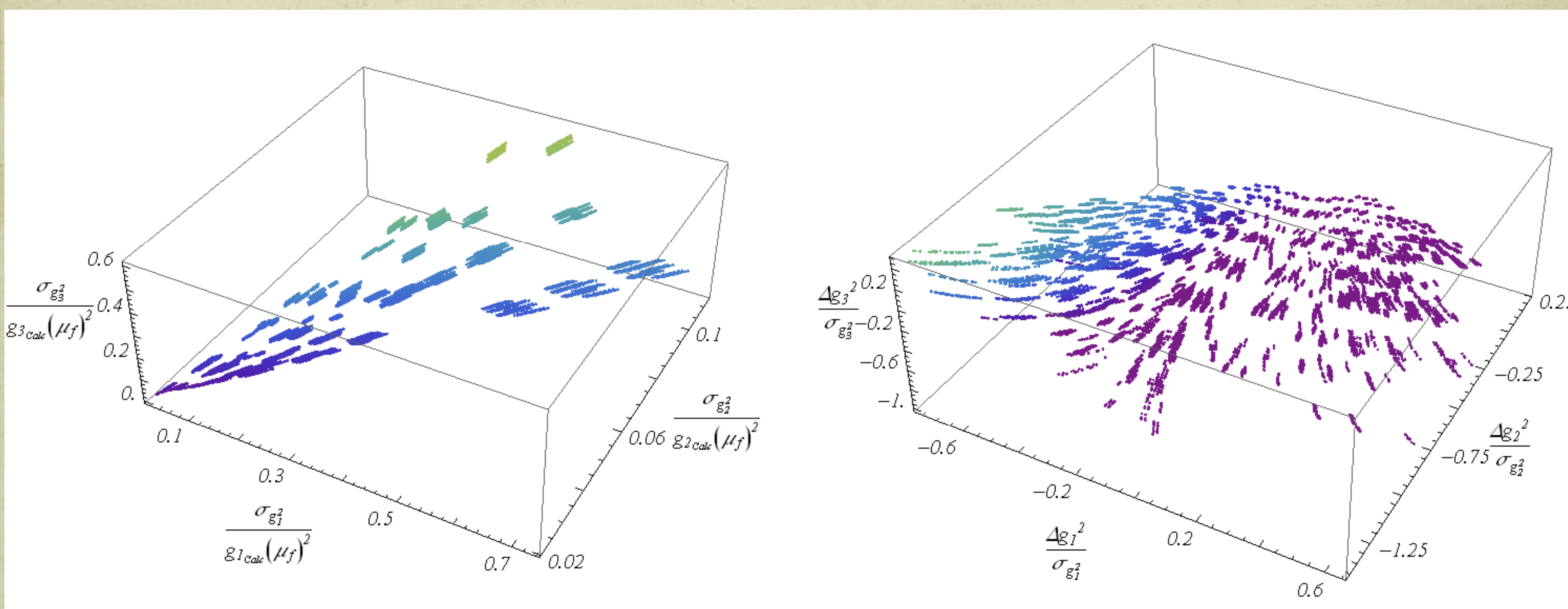
Large % errors in corrections to Higgs mass parameters expected when either is zero at input scale.

In above plots, Higgs mass parameter corrections are different with in error.

As seen from plot on the right, 2-loop contributions can be ignored for the extraction of these parameters.

This is true for both zero and non-zero corrections.

Determination of g_r at the messenger scale: $g_1^2(\mu_f) = -13/10\ D_{Y13H}\ /I_{Y\alpha}$



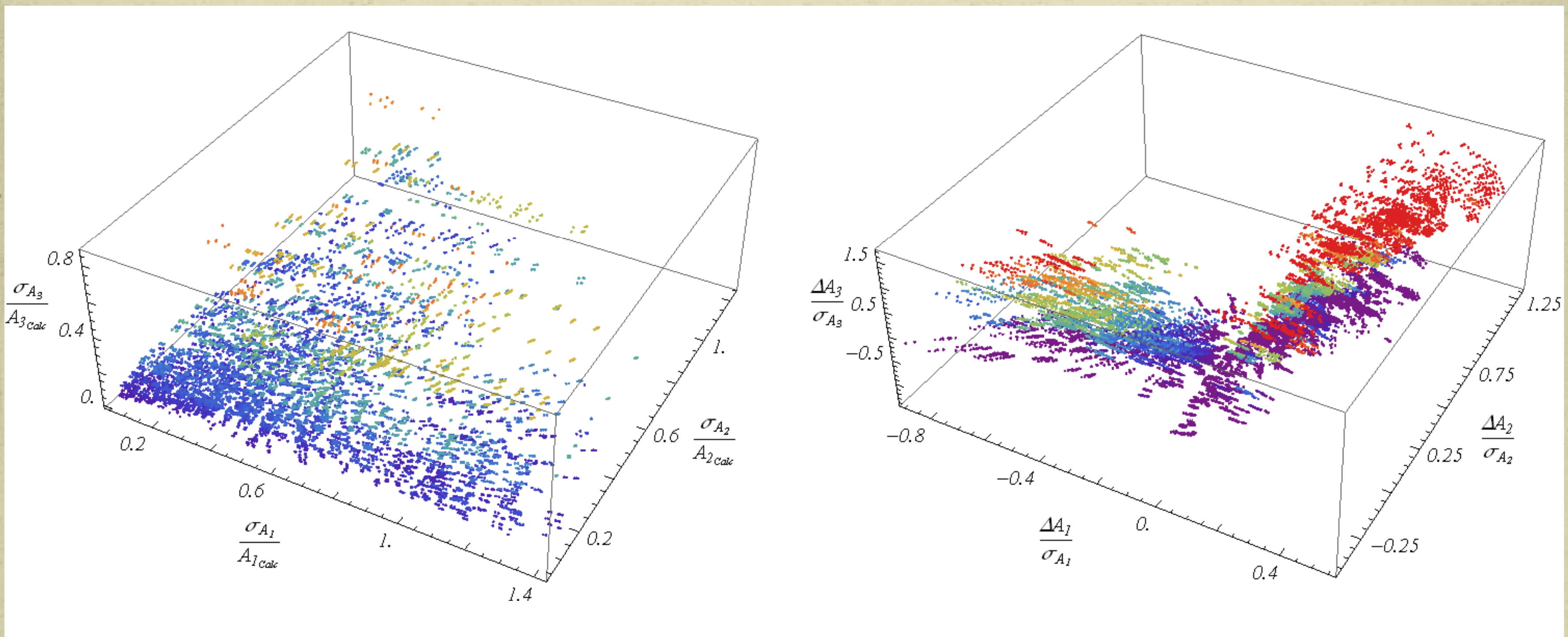
If the difference between the corrections to the Higgs up and down sector are determined to be zero within error, there will be large errors associated with the determination of the gauge couplings at the messenger scale.

However, actual value of $g_i^2(\mu_f)$ within **0.6 σ** of the calculated value of $g_i^2(\mu_f)$:

Can still determine a range for the couplings at the high scale.

Possible determination of A_r:

A_r extracted using B_r and g_r: indeterminacy for g_r transmits to A_r.



Actual value of A_r within **1.5 σ** of the calculated value of A_r : Can extract a range of consistent A_r.

Additionally, can find correlation between $A_{1,2}$ and $g_{1,2}$ with very small errors, using linear combination of invariants mentioned before:

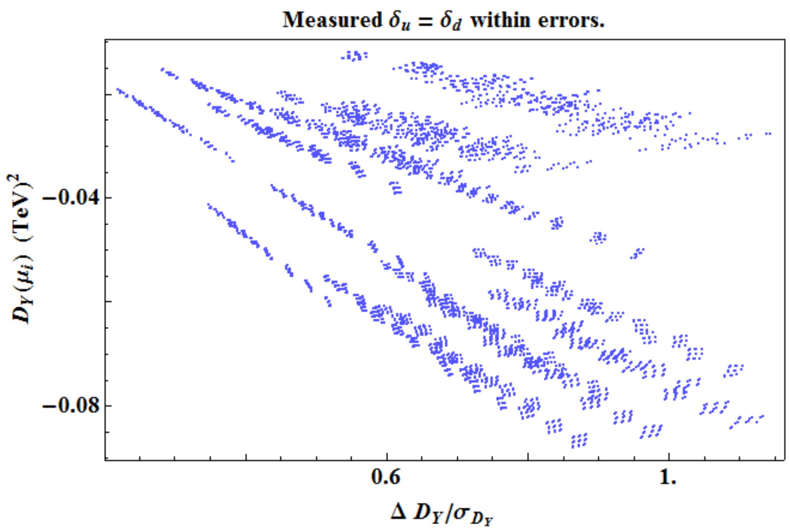
$$g_1^4 \frac{33}{10} A_1 + g_2^4 \frac{11}{2} A_2 = I_{M_{12}} - g_1^4 I_{B_1}^2 - 11 g_2^4 I_{B_2}^2$$

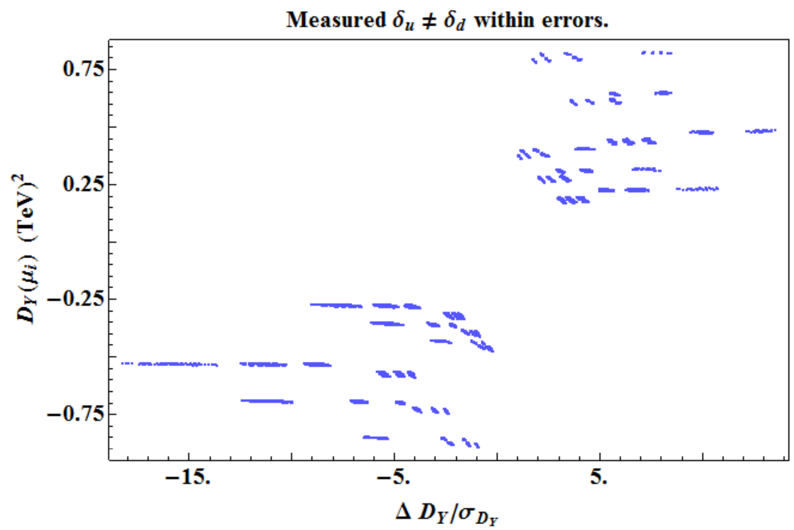
Outlook and Conclusions

- If SUSY is discovered at the LHC, that raises the question of the exact breaking of SUSY at some high scale.
- One would like to be able to probe this high scale phenomenon using TeV scale measurements.
- 1-loop RG Invariants provide a powerful tool to probe the high energy parameter space of models.
- Assuming an optimistic estimate of 1% measurement for the soft masses at the TeV scale, we checked that the 2-loop running does not destroy the invariance within experimental errors.
- These RGIs may determine the high energy scale.
- We can also check generic features like flavor blindness.
- Additionally, consistency with model parameter space can be probed.
- We ran numerical simulations scanning the parameter space of a certain class of models, known as GGM, demonstrating the power of using these invariants to probe physics beyond the reach of the LHC.
- This methodology may be used for other models, for eg: mSUGRA, anomaly mediation.

Back Up Slides

D_Y vs. the ratio of the running of D_Y and its expected error in measurements

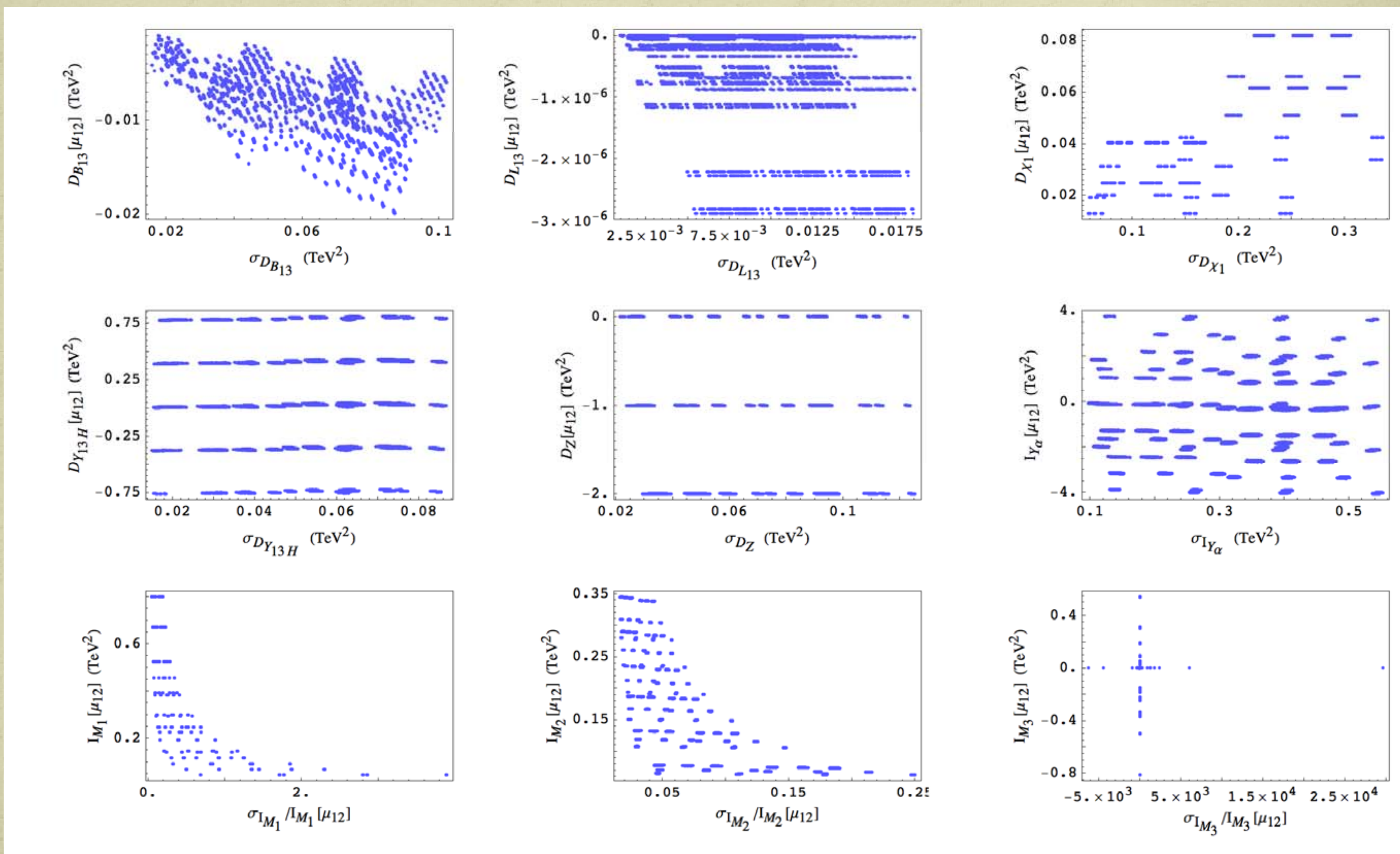




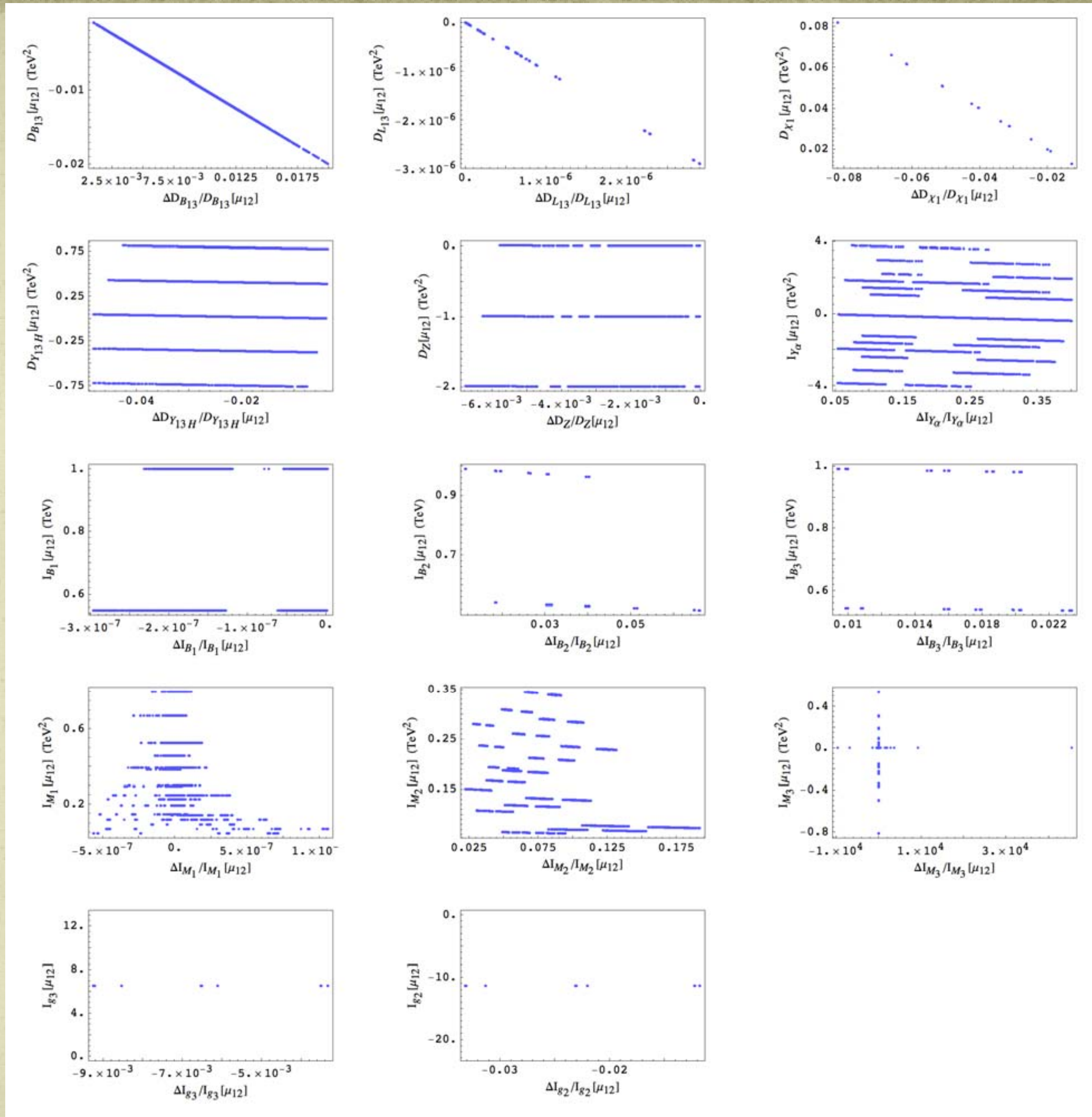
If minimal GGM, i.e., the Higgs mass parameters don't get corrections from supplemental SUSY breaking, D_Y running is smaller than the expected error in its measurement.

In non-minimal GGM, D_Y is not an invariant, hence as can be seen from the plot on the right, the running is comparable to or larger than the expected error. However, this would still give us information about whether it is consistent with zero or not.

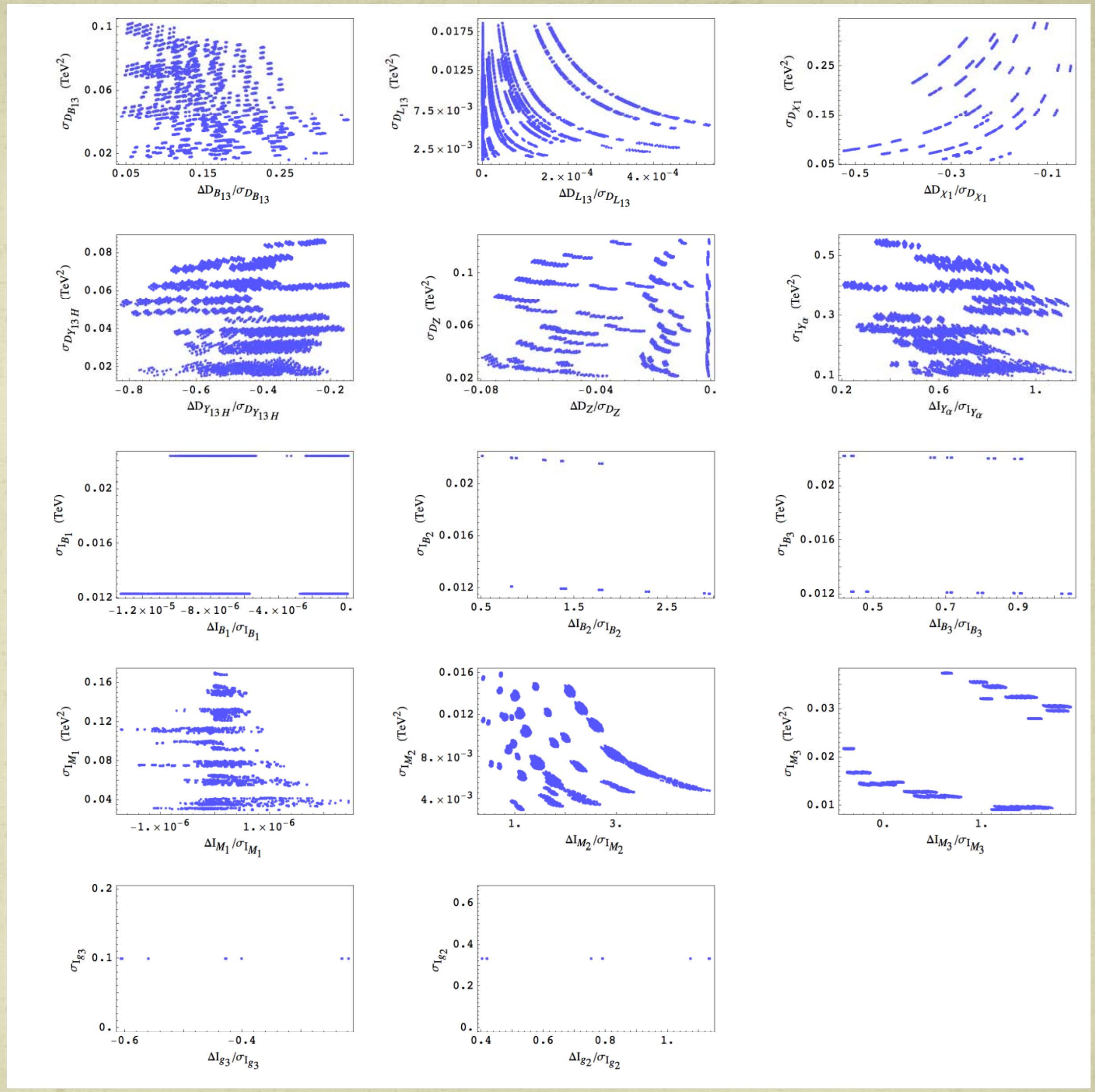
Invariants vs. σ



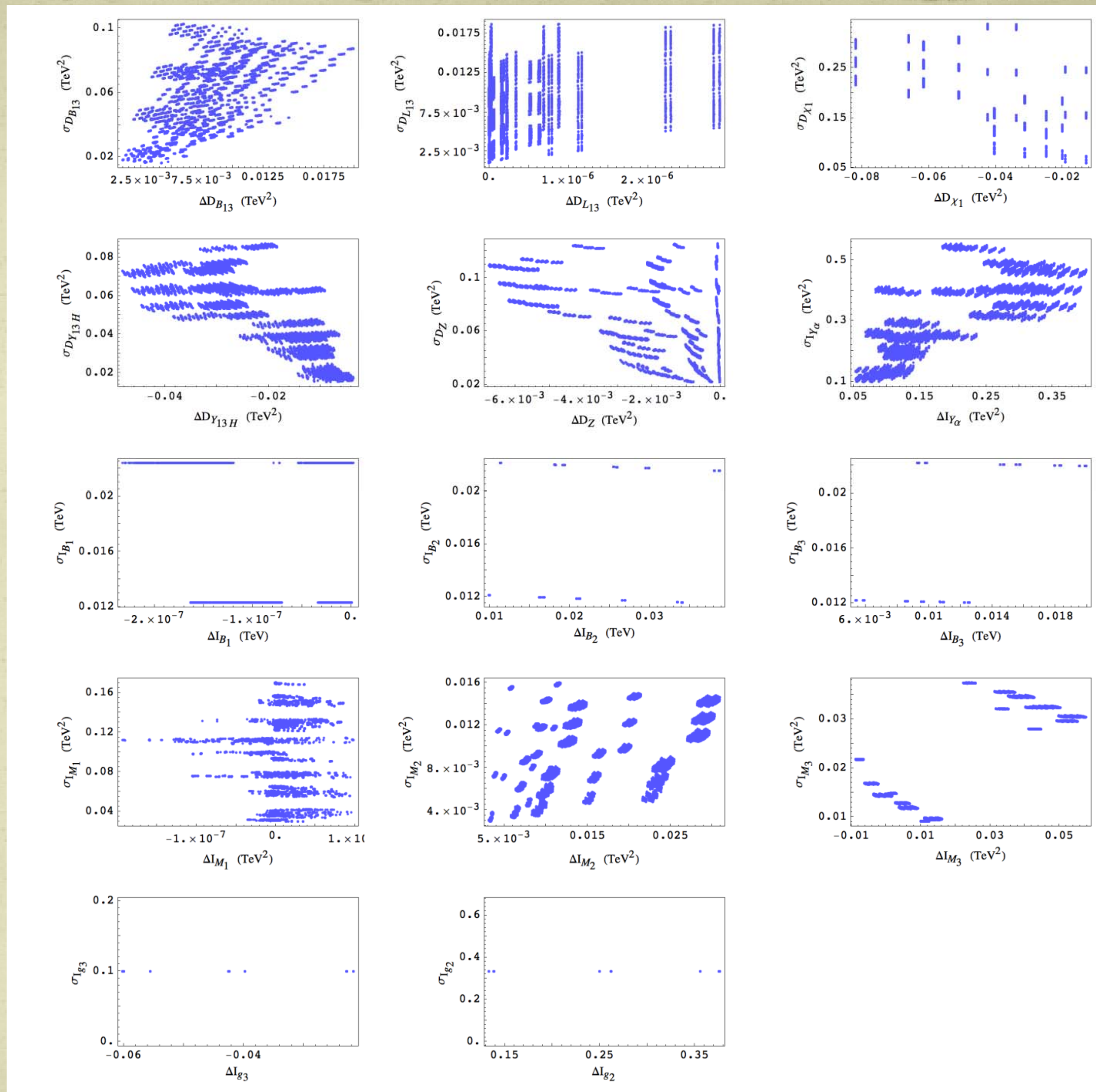
Invariants vs. 2-loop

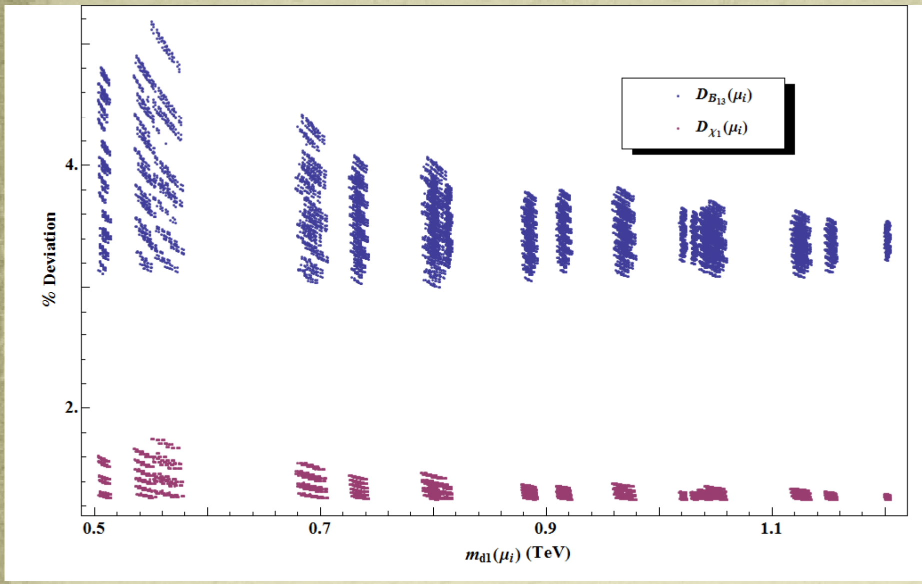


σ vs. Δ/σ

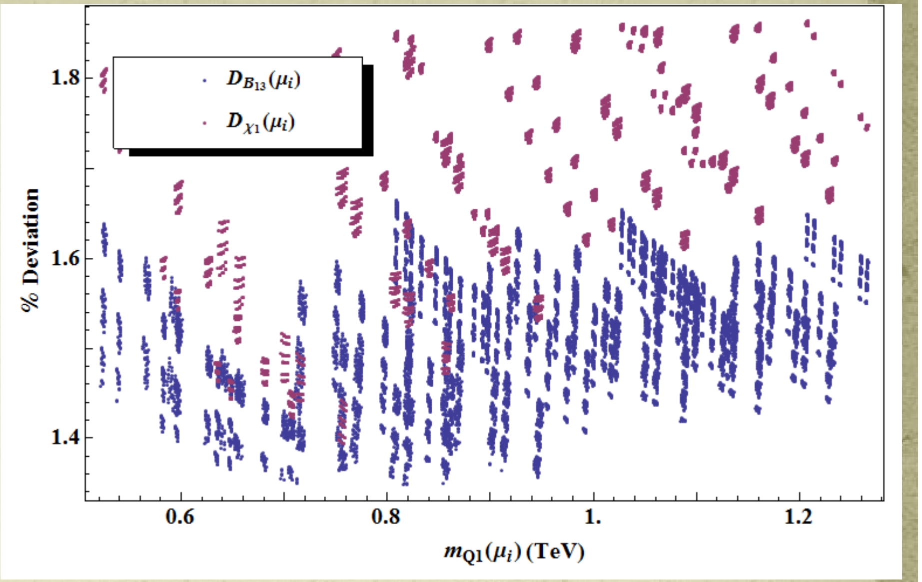


σ vs. Δ

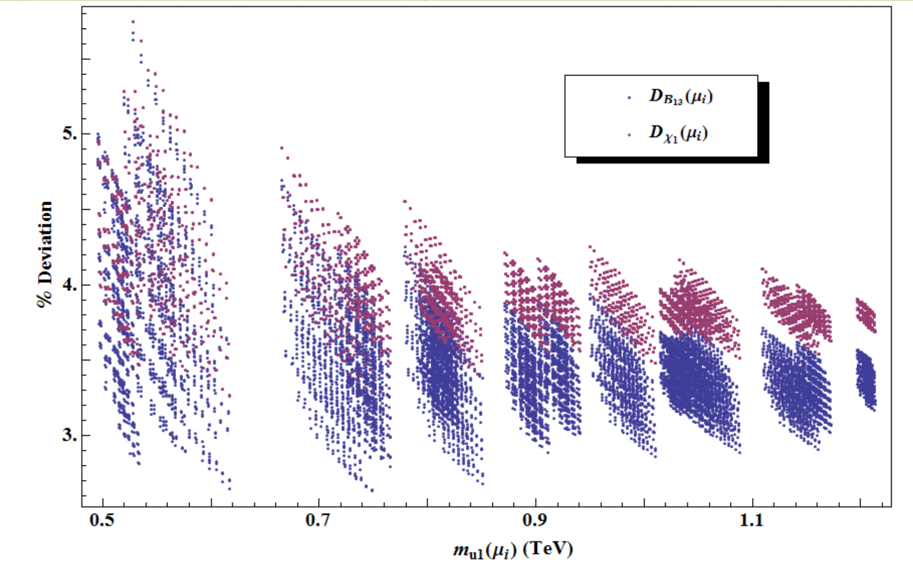




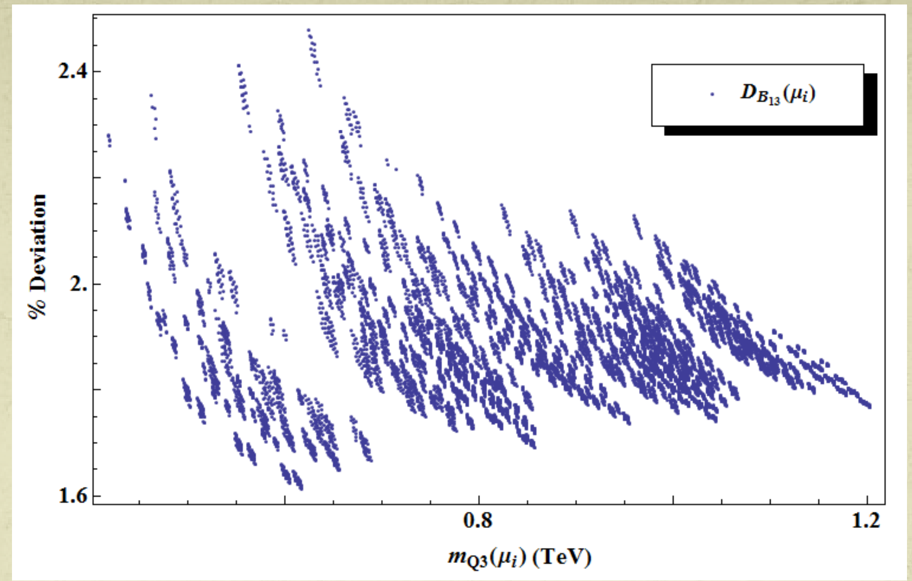
$D_{B_{13}}(\mu_i)$
$D_{\chi 1}(\mu_i)$
% Deviation
$m_{d1}(\mu_i)$ (TeV)



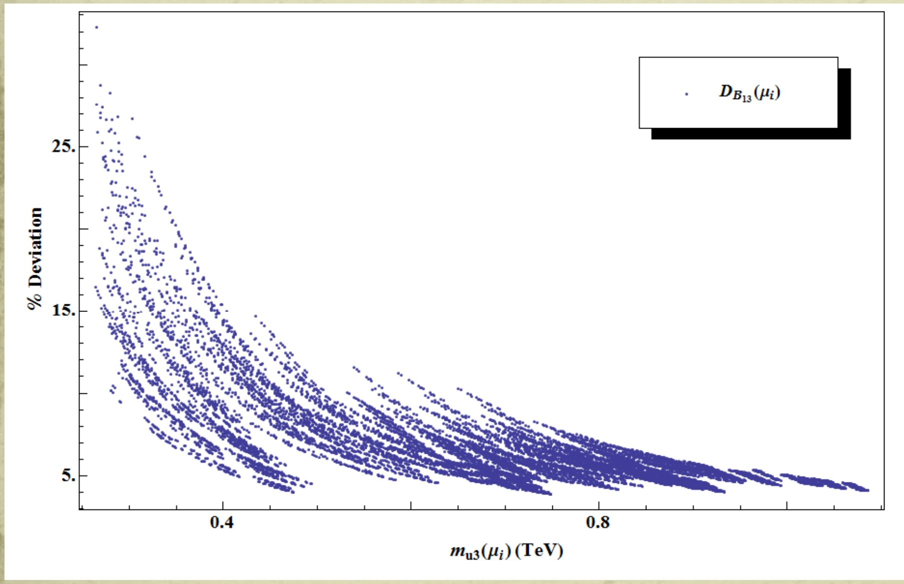
$D_{B_{13}}(\mu_i)$
$D_{\chi 1}(\mu_i)$
% Deviation
$m_{Q1}(\mu_i)$ (TeV)



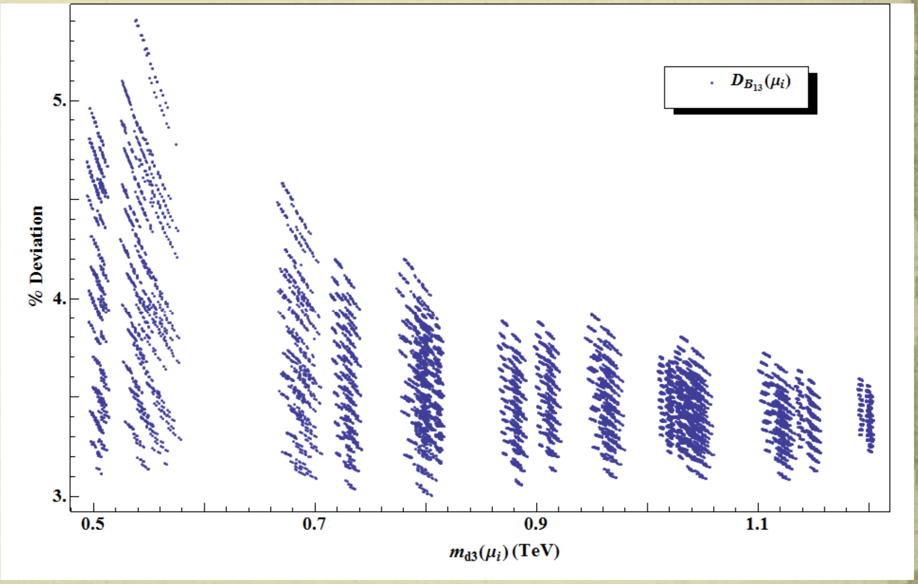
$D_{B_{13}}(\mu_i)$
$D_{\chi 1}(\mu_i)$
% Deviation
$m_{u1}(\mu_i)$ (TeV)



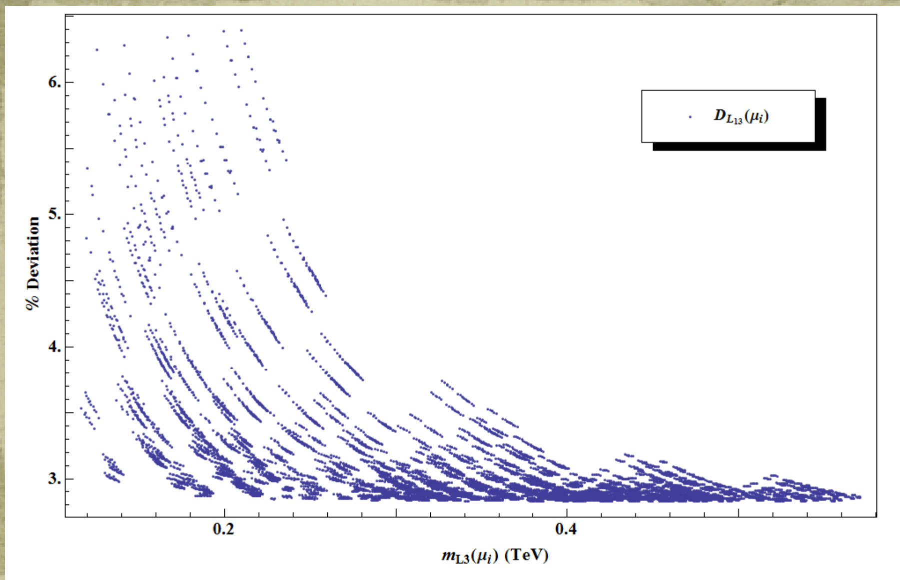
$D_{B_{13}}(\mu_i)$
% Deviation
2.4
2.
1.6
0.8
1.2
$m_{Q3}(\mu_i)$ (TeV)



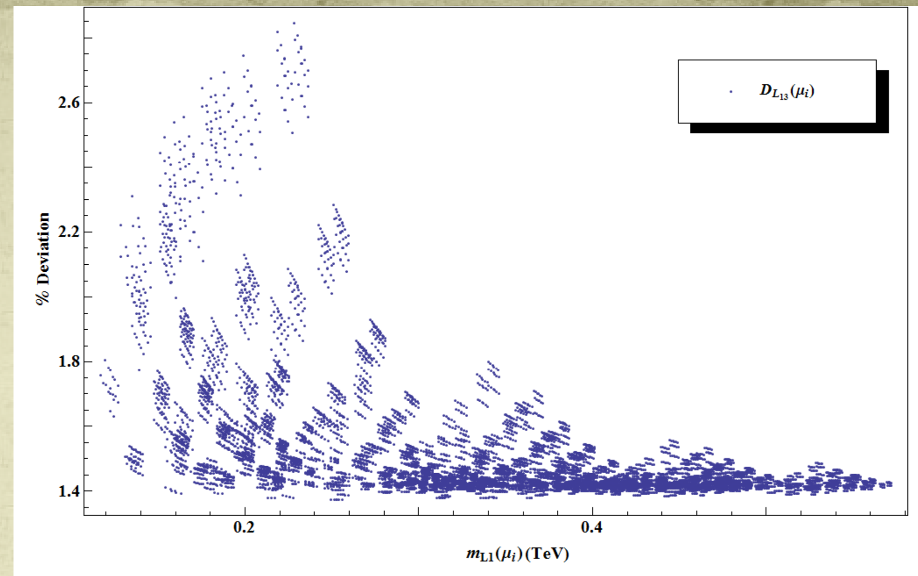
$D_{B_{13}}(\mu_i)$
% Deviation
25.
15.
5.
0.4
0.8
$m_{u3}(\mu_i)$ (TeV)



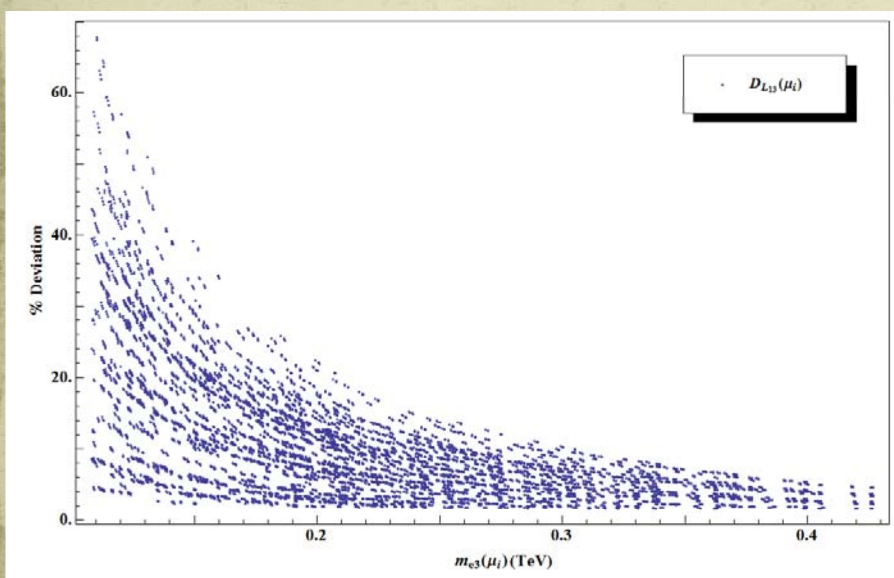
$D_{B_{13}}(\mu_i)$
% Deviation
5.
4.
3.
0.5
0.7
0.9
1.1
$m_{d3}(\mu_i)$ (TeV)



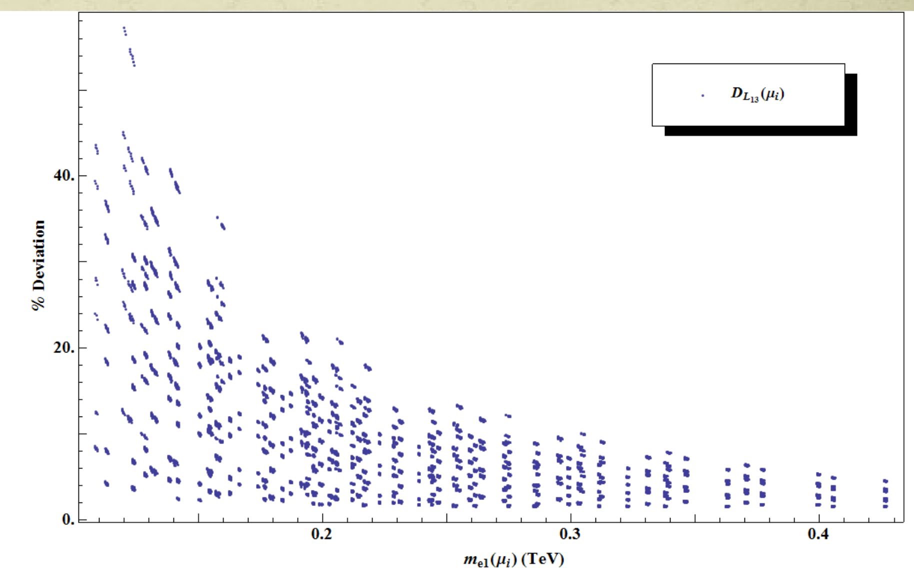
D_{L13}(μ_i)
% Deviation
6.
5.
4.
3.
0.2
0.4
m_{L3}(μ_i) (TeV)



D_{L13}(μ_i)
% Deviation
2.6
2.2
1.8
1.4
0.2
0.4
m_{L1}(μ_i) (TeV)



D_{L13}(μ_i)
% Deviation
60.
40.
20.
0.
0.2
0.3
0.4
m_{e3}(μ_i) (TeV)



D_{L13}(μ_i)
% Deviation
40.
20.
0.
0.2
0.3
0.4
m_{e1}(μ_i) (TeV)