Exploring new pE$_6$SSM signatures at LHC

Where is the LHC Higgs in E$_6$?
Where is the E$_6$ Z' at LHC?

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Projects in progress with:
Z': Sasha, Steve
h: Sasha, Matt, Marco et al.

Thursday Seminar
Southampton

Jan 17, 2013

Outline

1. The Model
   - MSSM
     - μ-problem
   - E_6SSM
     - More particles and more parameters

2. Where is the E_6 Z' at LHC?
   - A light Z' motivated by reduced fine-tuning
   - Experimental limits

3. Where is the LHC Higgs in E_6?
   - The mass
   - The couplings

4. Conclusions

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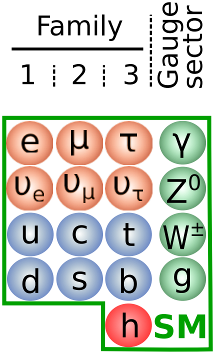
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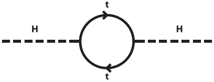
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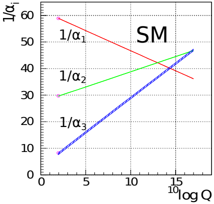
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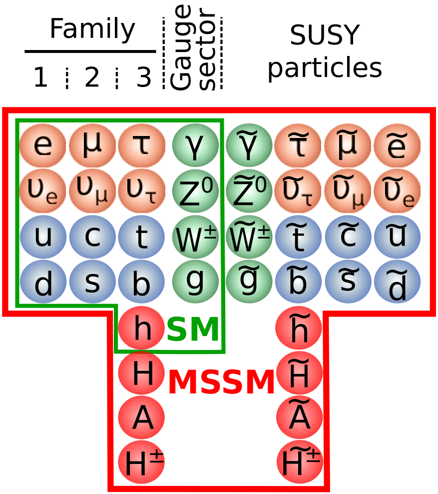
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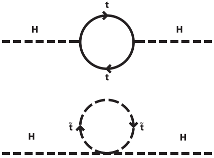
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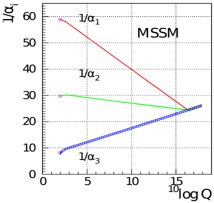
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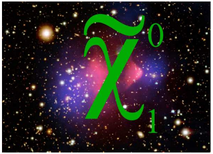

$\tilde{\chi}^0_1$

The μ-problem

MSSM superpotential:

$$W = y_u \bar{u} Q H_u + y_d \bar{d} Q H_d + y_e \bar{e} L H_d + \mu H_u H_d$$

Minimization of Higgs potential gives:

$$\frac{m_Z^2}{2} = -|\mu^2| + \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1}$$

where m_{H_d} and m_{H_u} are soft SUSY breaking Higgs mass parameters.

- We expect $\mu \sim m_{\text{soft}} \sim \mathcal{O}(\text{TeV})$
- But the μ-term is SUSY preserving so why

$$\mu \sim m_{\text{soft}} \quad \text{rather than} \quad \mu \sim M_{Pl} \quad ?$$

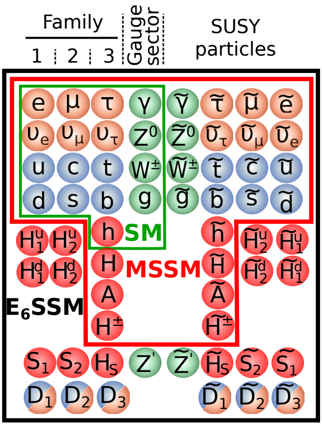
Solving the μ-problem

A common way to solve the μ problem is to introduce a scalar, S.

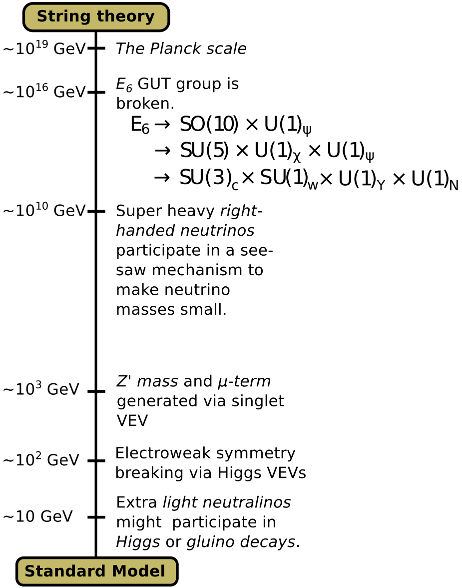
$$\lambda S H_u H_d \qquad \text{and} \qquad \langle S \rangle = \frac{s}{\sqrt{2}} \sim m_{\text{soft}} \sim 1\text{TeV} \qquad \Rightarrow \qquad \mu_{\text{eff}} = \frac{\lambda s}{\sqrt{2}}$$

But you have introduced a new global U(1) symmetry and broken it, resulting in a massless axion, which we haven't observed.

- **NMSSM:** A cubic term, S^3, is also added, breaking the U(1) down to a discrete Z_3. This could lead to cosmological domain walls and overclosure of the Universe.
- **USSM:** The U(1) is gauged and a massive Z' appear. However, the theory is not anomaly free.
- **$\mathbf{E_6}$SSM:** The gauged U(1) is a remnant of a broken E_6. Anomaly cancellation is assured by having particles in complete **27**s of E_6 at the TeV scale.



- String theory motivated model
- One extra surviving $U(1)'$
- Extra particles from complete **27**s of E_6



Field	Boson	Fermion	$SU(3)$	$SU(2)$	$U(1)$	$U(1)'$
Chiral	Spin 0	Spin 1/2				
Q^i	$\begin{pmatrix}\tilde{u}_L\\ \tilde{d}_L\end{pmatrix}^i$	$\begin{pmatrix}u_L\\ d_L\end{pmatrix}^i$	$\mathbf{3}$	$\mathbf{2}$	$\frac{1}{6}$	1
$\bar{u}^i$	$\tilde{u}_R^{*i}$	$u_R^{\dagger i}$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$-\frac{2}{3}$	1
$\bar{d}^i$	$\tilde{d}_R^{*i}$	$d_R^{\dagger i}$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$\frac{1}{3}$	2
L^i	$\begin{pmatrix}\tilde{\nu}_L\\ \tilde{e}_L\end{pmatrix}^i$	$\begin{pmatrix}\nu_L\\ e_L\end{pmatrix}^i$	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$	2
$\bar{e}^i$	$\tilde{e}_R^{*i}$	$e_R^{\dagger i}$	$\mathbf{1}$	$\mathbf{1}$	1	1
$\bar{N}^i$	$\tilde{N}_R^{*i}$	$N_R^{\dagger i}$	$\mathbf{1}$	$\mathbf{1}$	0	0
S^i	$\tilde{S}^{*i}$	$S^{\dagger i}$	$\mathbf{1}$	$\mathbf{1}$	0	5
H_u^i	$\begin{pmatrix}H_u^+\\ H_u^0\end{pmatrix}^i$	$\begin{pmatrix}\tilde{H}_u^+\\ \tilde{H}_u^0\end{pmatrix}^i$	$\mathbf{1}$	$\mathbf{2}$	$\frac{1}{2}$	-2
H_d^i	$\begin{pmatrix}H_d^0\\ H_d^-\end{pmatrix}^i$	$\begin{pmatrix}\tilde{H}_d^0\\ \tilde{H}_d^-\end{pmatrix}^i$	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$	-3
D^i	$\tilde{D}^{*i}$	$D^{\dagger i}$	$\mathbf{3}$	$\mathbf{1}$	$-\frac{1}{3}$	-2
$\bar{D}^i$	$\tilde{\bar{D}}^{*i}$	$\bar{D}^{\dagger i}$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$\frac{1}{3}$	-3
Gauge	Spin 1	Spin 1/2				
g	g	$\tilde{g}$	$\mathbf{8}$	$\mathbf{1}$	0	0
W	$W^{\pm,0}$	$\tilde{W}^{\pm,0}$	$\mathbf{1}$	$\mathbf{3}$	0	0
B	B	$\tilde{B}$	$\mathbf{1}$	$\mathbf{1}$	0	0
B'	B'	$\tilde{B}'$	$\mathbf{1}$	$\mathbf{1}$	0	0

E_6SSM

New features:

- Gauge group: $U(1)'$
- Fields: $N, S, D, \bar{D}, B'$
- Families in Higgs sector

Summarising the model

pE_6SSM involves

- More particles

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- **More interesting signatures**

Summarising the model

pE_6SSM involves

- More particles
- More VEVs
- More terms
- More couplings
- More computing hours
- More (broken) symmetry
- More interactions
- More constraints
- **More interesting signatures**
- More fun!

Why the p?

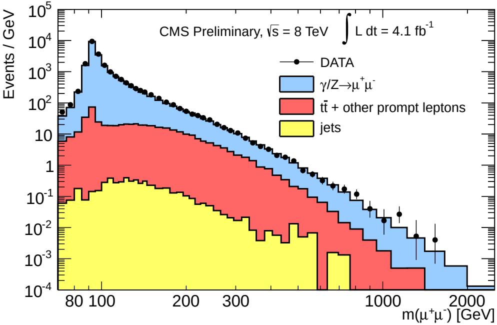
- To emphasize that we are not studying the GUT constrained E_6SSM (cE_6SSM) I will dentote this unconstrained, electro-weak scaled model as **the phenomenological E_6SSM (pE_6SSM)** in analogy with the pMSSM
  - We are using a CalcHEP model which is available on HEPMDB
  - Electro-weak scale couplings and soft SUSY breaking parameters are input parameters

Where is the E_6 Z' at the LHC?

Collaborators: Sasha and Steve

Why are we interested in $Z's$?

- A lot of models predict an extra $U'(1)$
  - Extra dimensions, Technicolour, GUTs...
- Z's may provide clear dilepton signatures
- Z's are typically expected to be light (within reach of the LHC)
- But no bumps so far...



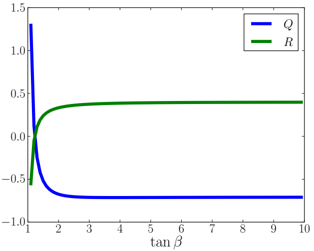
The Higgs potential minimisation condition

$$\frac{M_Z^2}{2} = -|\mu|^2 \quad + \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1}$$

$$\Downarrow$$

$$\left(1 - \frac{g_1'^2}{\bar{g}^2} Q(\tan\beta)\right)\frac{M_Z^2}{2} = -|\mu_{\text{eff}}|^2 + \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1} + \frac{M_{Z'}^2}{2} R(\tan\beta)$$

- $M_{Z'}$ is a new independent source of fine-tuning
- In general, if the Higgs states carry $U(1)'$ charges the Z' mass will appear in the Higgs potential minimization conditions



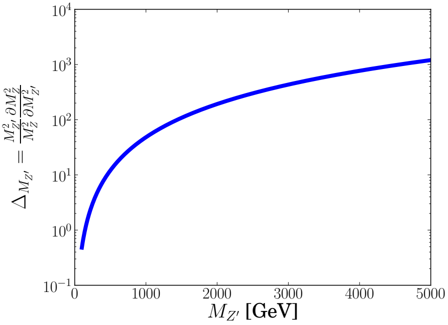
Fine-tuning

Defining fine-tuning with respect to a model parameter α as the ratio of relative change of M_Z^2 to the relative change of α

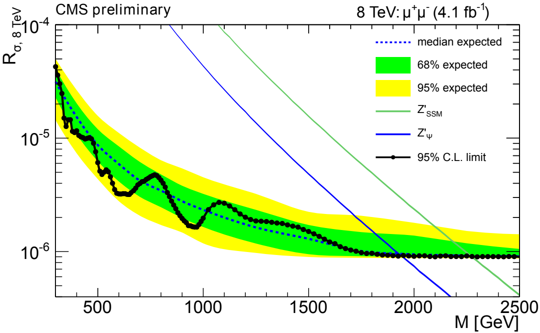
$$\Delta_\alpha = \frac{\frac{\Delta M_Z^2}{M_Z^2}}{\frac{\Delta\alpha}{\alpha}} = \frac{\alpha}{M_Z^2}\frac{\Delta M_Z^2}{\Delta\alpha} \to \frac{\alpha}{M_Z^2}\frac{\partial M_Z^2}{\partial\alpha}$$

- We consider $\alpha = M_{Z'}^2$
- The overall fine-tuning is the maximum of all sources

$$\Delta = \max_\alpha(\Delta_\alpha)$$

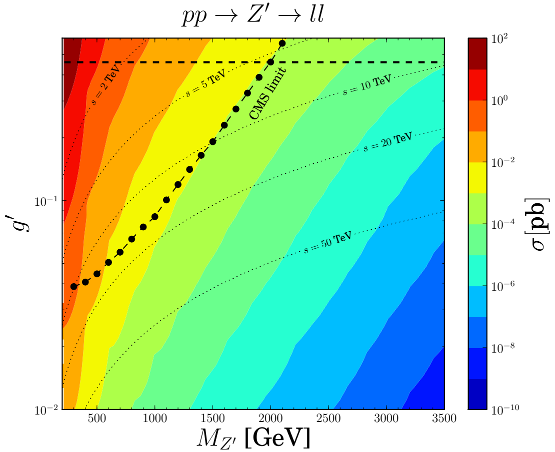


Experimental limits on cross sections



- Exclusions are typically made on the cross section $\sigma_{Z^{prime}}$ (or its ratio, R_σ to the Z cross section)
- We are interested in the limits on the coupling g'

Experimental limits in the $M_{Z'} - g'$ plane



- For GUT predicted value of g' CMS limit is

$$M_{Z'} \gtrsim 2\,TeV$$

- Low-mass Z' is allowed if the coupling g' is reduced

$g'/0.46$	1	1/2	1/10	1/15
$M_{Z'}/TeV >$	2	1.6	0.5	~ 0.2
$\Delta_{M_{Z'}} >$	192	123	12	~ 1
$s/TeV >$	5.5	8.8	13.7	~ 8

$$M_{Z'}^2 = g_1'^2 v^2 \left(\tilde{Q}_1^2 \cos^2\beta + \tilde{Q}_2^2 \sin^2\beta \right) + g_1'^2 \tilde{Q}_S^2 s^2 \approx g_1'^2 \tilde{Q}_S^2 s^2$$

Summary of light (E_6) Z'

- Not excluded by LHC data
- We should remember the weak coupling regime as well as the large mass regime
- Motivated by less fine-tuning
- We should remember the other sources of fine-tuning as well. When decreasing the Z' mass limit by decreasing the coupling we are pushing up the singlet VEV which appears in

$$\mu_{\rm eff} = \frac{\lambda s}{\sqrt{2}}.$$

$\rightarrow$ we have to decrease λ together with g'.
We are investigating what other implications this scenario has...

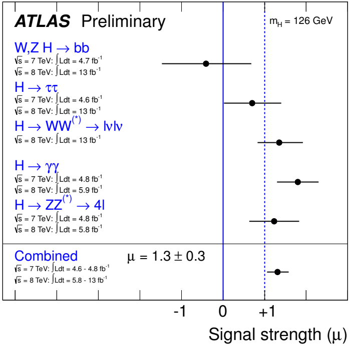
Where is the LHC Higgs in the E_6SSM parameter space?

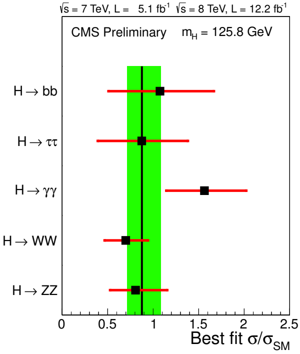
Collaborators: Sasha, Matt, Marco[Dresden] et al.

The LHC boson

- A new boson is discovered
- The measurements are so far in good agreement with the SM
- Is statistics or BSM phyics the cause for the $\gamma\gamma$ excess?
- We are investigating how and where the pE_6SSM can accommodate the measured mass and couplings

November 2012:





The E_6SSM Higgs mass

Important tree-level contributions to the lightest Higgs mass are

$$M_h^2 = \frac{\lambda^2 v^2}{2} \sin^2 2\beta + M_Z^2 \cos^2 2\beta + g' v^2 (Q_1 \cos^2 \beta + Q_2 \sin^2 \beta)^2 + \dots$$

In our choice of parameterisation the Higgs mass is a function of 6 parameters and take into account two-loop effects

$$M_h = M_h(M_A, \tan\beta, M_{\tilde{q}}, A_t, s, \lambda)$$

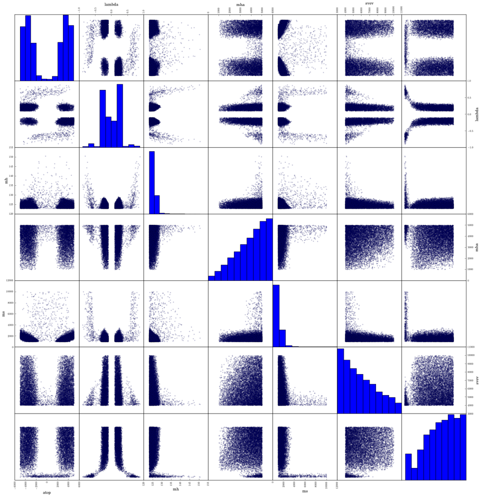
- M_A is the CP-odd Higgs mass $\leftrightarrow$ soft A_λ in the SH_uH_d coupling
- $\tan\beta$ is the ratio of Higgs VEVs
- $M_{\tilde{q}}$ is a common soft squark mass scale
- A_t is the soft parameter in the stop coupling $\tilde{t}\tilde{\bar{t}}H_u \leftrightarrow$ stop mixing X_t
- s is the VEV of the singlet field S
- λ is the coupling in SH_uH_d

Where to find $M_h \approx 125$ GeV

- Allowed regions were found by a broad scan

parameter	min	max
$\tan\beta$	1.1	20
λ	0.1	0.9
A_t	-5 TeV	5 TeV
s	1 TeV	10 TeV
M_A	1 TeV	5 TeV
$M_{\tilde{q}}$	1 TeV	10 TeV

- Complicated parameter space but some correlations can be seen



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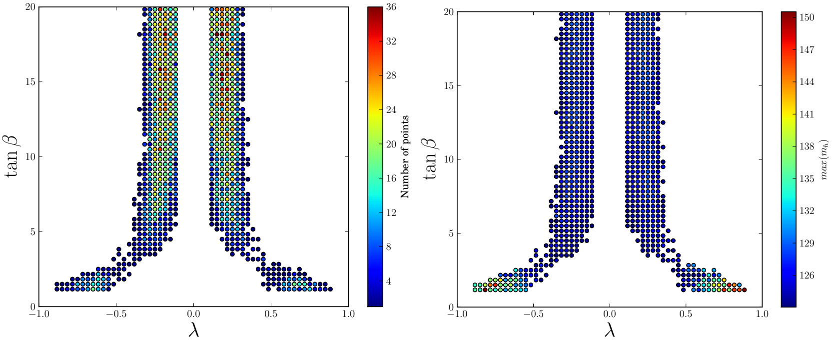
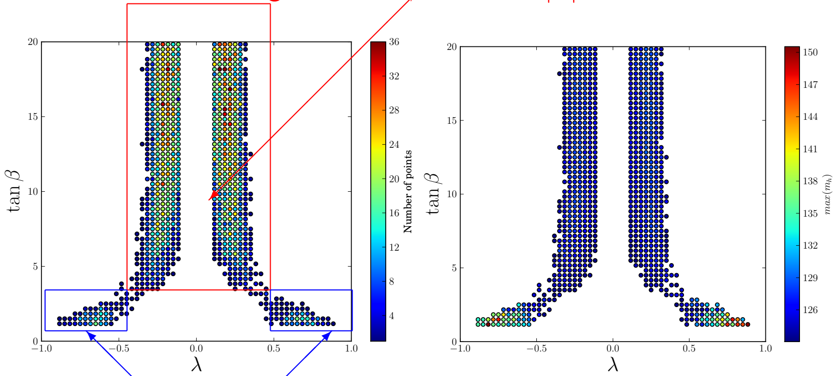


$$M_h^2 = \frac{\lambda^2 v^2}{2} \sin^2 2\beta + M_Z^2 \cos^2 2\beta + g'\, v^2 (Q_1 \cos^2 \beta + Q_2 \sin^2 \beta)^2 + \ldots$$

Where to find $M_h \approx 125$ GeV

Region X: $\tan\beta > 4$ and $|\lambda| < 0.4$

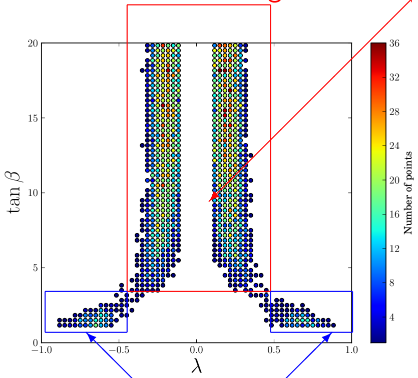


$$M_h^2 = \frac{\lambda^2 v^2}{2} \sin^2 2\beta + M_Z^2 \cos^2 2\beta + g'^2 v^2 (Q_1 \cos^2\beta + Q_2 \sin^2\beta)^2 + \ldots$$

Region Y: $\tan\beta < 4$ and $|\lambda| > 0.4$

Where to find $M_h \approx 125$ GeV

Region X: $\tan\beta > 4$ and $|\lambda| < 0.4$



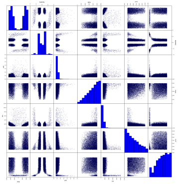
- For $|\lambda| \gtrsim 0.4$, λ contributes positively to the Higgs mass for $\tan\beta \lesssim 4$ and negatively for $\tan\beta \gtrsim 4$
- For $|\lambda| \lesssim 0.4$, a large Higgs mass rely on large $\tan\beta$ to maximise the contribution proportional to M_Z (the $U(1)_Y$ and $U(1)_N$ D-terms)

$$M_h^2 = \frac{\lambda^2 v^2}{2} \sin^2 2\beta + M_Z^2 \cos^2 2\beta + g'\, v^2 (Q_1 \cos^2\beta + Q_2 \sin^2\beta)^2 + \ldots$$

Region Y: $\tan\beta < 4$ and $|\lambda| > 0.4$

The two allowed regions

- The found correlations constrain the two regions further:



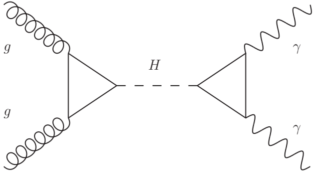
$\Rightarrow$

	X	Y
$\tan\beta$	> 4	< 4
$\lvert\lambda\rvert$	< 0.4	> 0.4
$\lvert A_t\rvert$	> 2 TeV	-
s	-	< 7.5 TeV
M_A	-	> 3 TeV
$M_{\tilde{q}}$	< 3.5 TeV	-

- We perform separate scans for these regions when considering the constraints from the Higgs coupling measurements

The E_6SSM Higgs couplings

- The leading contributions to the Hgg and $H\gamma\gamma$ couplings appear at loop level



- E_6SSM introduces a lot of new particles to these loops
  - Hgg: squarks, **diquarks, diquarkinos**
  - $H\gamma\gamma$: squarks, sleptons, **diquarks, diquarkinos, charginos, charged Higgses**
- More parameters have to be added to the scan

		min	max
$S D\bar{D}$ coupling	$\kappa = \kappa_{i=1,2,3}$	0.1	1
soft scalar $S D\bar{D}$ coupling	A_κ	-5 TeV	5 TeV
soft diquark mass	M_{DQ}	2 TeV	10 TeV
gaugino (wino) mass	M_2	0.1 TeV	1 TeV
soft inert Higgs masses	M_{H_α}	0.5 TeV	5 TeV

Excluding points with a χ^2 function

- We define a χ^2 function with three terms corresponding to the $\gamma\gamma$, ZZ and WW channel

$$\chi^2 = \sum_{i=Z,W,\gamma} \frac{(\mu_i' - \mu_i)^2}{\sigma_i^2}$$

- The best fit for the signal strengths μ_i and their errors σ_i are taken from ATLAS
- We then calculate

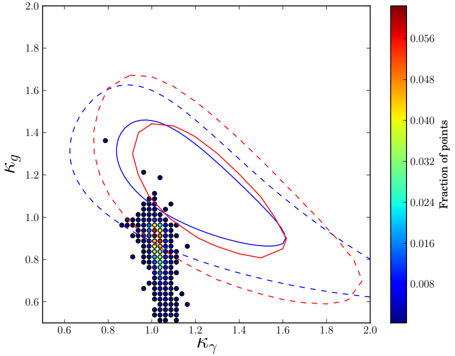
$$\mu_i' = \frac{\Gamma_h}{\Gamma_h^{\mathrm{SM}}} \frac{\mathrm{Br}_g}{\mathrm{Br}_g^{\mathrm{SM}}} \frac{\mathrm{Br}_i}{\mathrm{Br}_i^{\mathrm{SM}}}$$

for each scanned point and rule it out if $\chi^2 >6$, which corresponds to 95% CL in this case

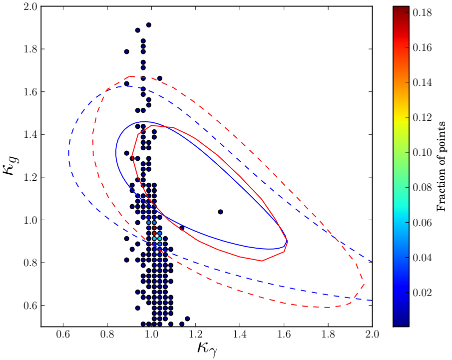
gg and $\gamma\gamma$ couplings

- No exclusions are made from the plots below
- These plots indicates how well our approximation of the χ^2 function agrees with ATLAS (in the case of all other couplings =SM)

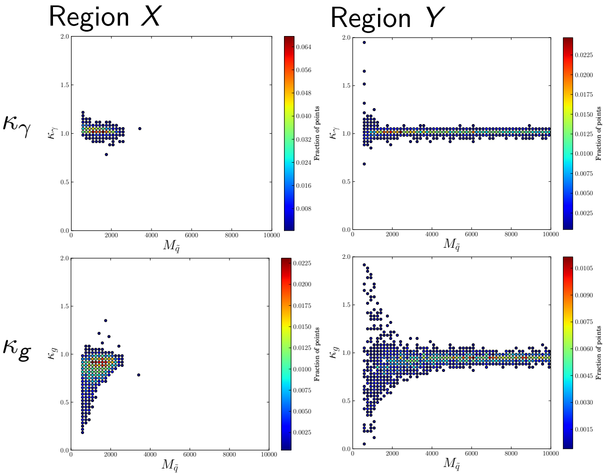
Region X



Region Y

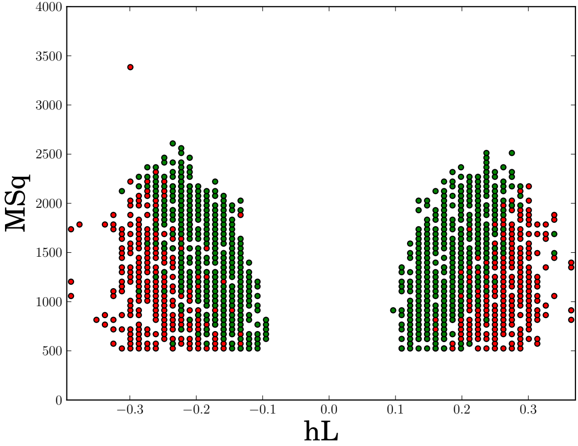


gg and $\gamma\gamma$ couplings and $M_S = M_{\tilde{q}} = M_{\tilde{l}}$



- Light sfermions ($M_S \lesssim 1$ TeV) are needed to give large $\gamma\gamma$ enhancements
- Light squarks ($M_{\tilde{q}} \lesssim 2$ TeV) are needed to cause large gg deviations

By requiring $\chi^2(\mu'_\gamma, \mu'_W, \mu'_Z) > 6$ for excluded points we can make projection of excluded areas in planes of input parameters:

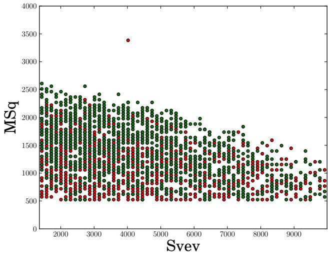


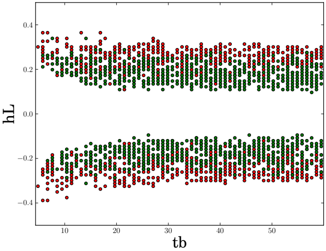
For example $M_{\tilde{q}} - \lambda$ in region X:
The coupling measurements push squark masses up and the coupling λ down

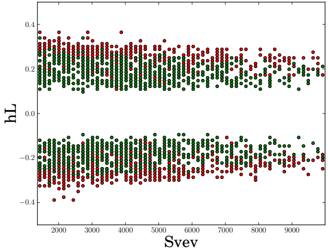
hL=λ
MSq=$M_{\tilde{q}}$

More examples from Region X

- We may see some slight preference of
  - smaller s
  - larger $\tan\beta$
- Need more data to place strong constraints from couplings measurements







Summary of the Higgs measurements

- The mass measurement alone places quite strict and interesting constraints on the parameter space
- The couplings place some extra constraints but more data is needed
- We are working on including the $\tau\tau$ and bb channels, which are important measurements, especially for large $\tan\beta$
- For most points the Higgs appear to be very MSSM and SM like

Conclusions

- In the absence of any hints of gluinos (or squarks) and recalling that these are more difficult channels in the E_6SSM than in the MSSM we might see the hints of this model first in Z' searches and Higgs measurements.
- A light, weakly coupled Z' is motivated by fine-tuning arguments and may still be found among the backgrounds at the LHC
- The measurements of the Higgs mass and couplings can provide hints of BSM physics. We are defining the regions of parameter space which can accommodate the measured signal strengths.
- A rigorous combination of Z' and Higgs constraints would be powerful and will be my next step