Search for Discoverable SUSY Models

DAMARA Evaluation Meeting

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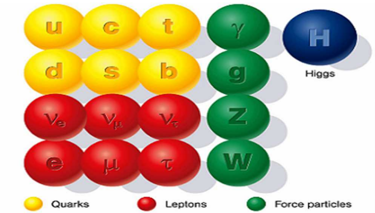
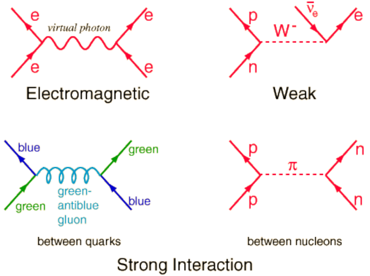
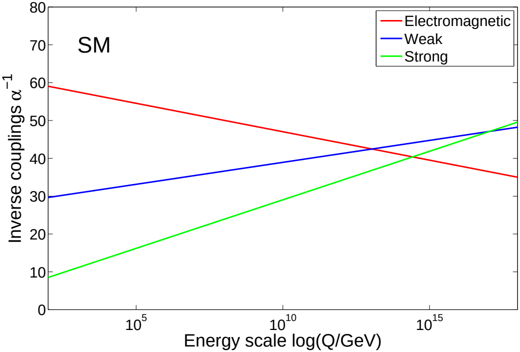
- The standard model of particle physics (SM) is the current framework for describing subatomic physics
- Fundamental constituents described by quantized fields (Quantum Field Theory)
- Particles are described as exitations of the fields
- Experimentally very successfull, but cannot be the full story

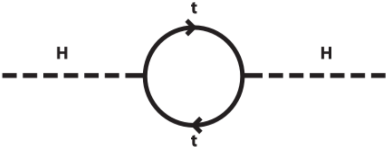




- The Standard Model does not include gravity
- Effective low energy description
  (Quantum Gravity: $M_{\mathrm{Planck}} \sim 10^{19}$ GeV $\sim 10^{17} M_Z$)
- SM couplings energy dependent, suggests unification of forces
  (Grand Unified Theories: $M_{\mathrm{GUT}} \sim 10^{16}$ GeV $\sim 10^{14} M_Z$)



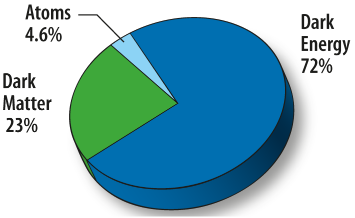
- Masses also energy dependent
- fermion & gauge bosons protected by symmetry $\Delta m(Q) \propto \ln(Q)$
- No symmetry protects the Higgs mass parameter $\Delta m^2(Q) \propto Q^2$



- Low energy higgs mass $M_H^2(M_Z) \sim (100\text{GeV})^2$
- If SM breaks down at M_{Pl} then one would expect $M_H^2(M_{Pl}) \sim M_{Pl}^2$

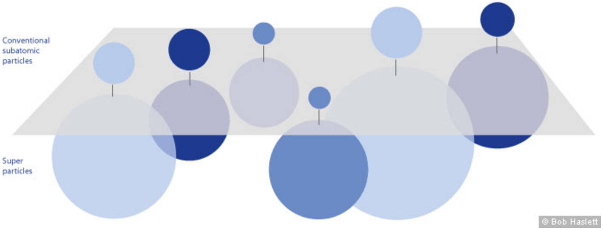
$$\frac{|M_H^2(M_{Pl}) - \Delta M_H^2(M_{Pl})|}{M_H^2(M_{Pl})} \sim 10^{-34} \quad \text{(Extreme fine tuning !)}$$

- Cosmology and astrophysics: 23% of the energy in the universe consist of unknown form of matter (Dark Matter) which behaves similar to ordinary matter but interacts very weakly.



- Dark matter (DM) only indirectly inferred from gravitational effects
- DM particles: Stable and weak interactions with ordinary matter
- SM neutrinos contribute but not enough, new physics needed

- Supersymmetry (SUSY) relates fermions to bosons



- The Minimal Supersymmetric Standard Model (MSSM) provides the simplest supersymmetric extension of the standard model.

- The MSSM assigns superpartners (sparticles) to each of the SM particles with similar properties but different spin.

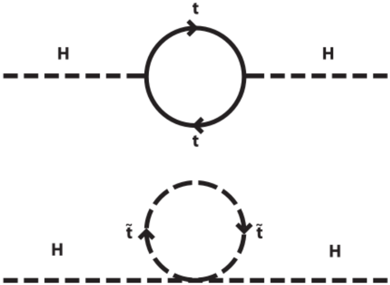
FERMIONS			BOSONS		
spin	Name	Symbols	Name	Symbols	spin
½	leptons	e, ν_{eL}	sleptons	$\tilde{e}_L, \tilde{e}_R, \tilde{\nu}_{eL}$	0
		$\mu, \nu_{\mu L}$		$\tilde{\mu}_L, \tilde{\mu}_R, \tilde{\nu}_{\mu L}$	
		$\tau, \nu_{\tau L}$		$\tilde{\tau}_L, \tilde{\tau}_R, \tilde{\nu}_{\tau L}$	
½	quarks	u, d	squarks	$\tilde{u}_L, \tilde{d}_L, \tilde{u}_R, \tilde{d}_R$	0
		c, s		$\tilde{c}_L, \tilde{s}_L, \tilde{c}_R, \tilde{s}_R$	
		t, b		$\tilde{t}_L, \tilde{b}_L, \tilde{t}_R, \tilde{b}_R$	
½	gluinos	$\tilde{g}$	gluons	g	1
½	charginos	$\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^{\pm}$	EW bosons	$\gamma, Z^0, W^{\pm}$	1
½	neutralinos	$\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$	higgs	$h^0, H^0, A^0, H^{\pm}$	0

SM particles (observed)	SM particles (not yet observed)	Super Partners (not yet observed)

- Symmetry called R-parity introduced to avoid interactions which lead to proton decay and other unobserved processes.
- extending SM symmetries to include supersymmetry helps solve many of the problems mentioned earlier.

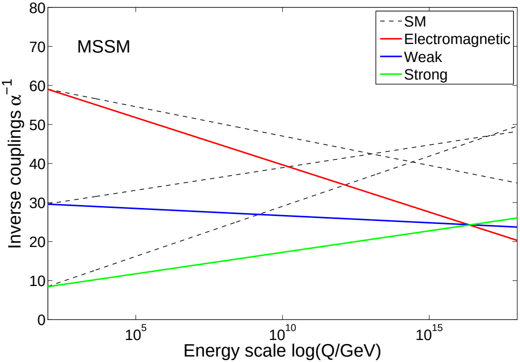
- R-parity $\rightarrow$ Lightest Supersymmetric Particle (LSP) is stable
- If LSP is neutral it has exactly the properties associated with dark matter
- Common LSP Dark Matter candidates:
  - **Neutralino** $\tilde{\chi}_0^1$ (spin 1/2)
    Viable SUSY DM candidate in a variety of models (mSUGRA, GMSB,...)
  - **Gravitino** $\tilde{g}$ (spin 3/2)
    Models with gravitno dark matter much more heavily constrained

- Supersymmetry shields the Higgs boson mass from large corrections with increasing energy
- Higgs-sparticle interactions gives equal corrections of opposite sign.



- corrections cancel exactly! (unbroken SUSY)

- Finally Supersymmetry also improves the convergence of coupling constants



- Unification occurs at $M_{GUT} \approx 2 \cdot 10^{16}$, SUSY discovery would be a strong indication of grand unified theory at M_{GUT}

- Exact SUSY implies equal masses for sparticles and particles
- Sparticles not detected → must be heavy, $M_{\tilde{s}} \gtrsim 100 GeV$
- To avoid spoiling naturalness, SUSY breaking terms must be "soft".
- "Soft" SUSY breaking → logarithmic corrections to Higgs mass.

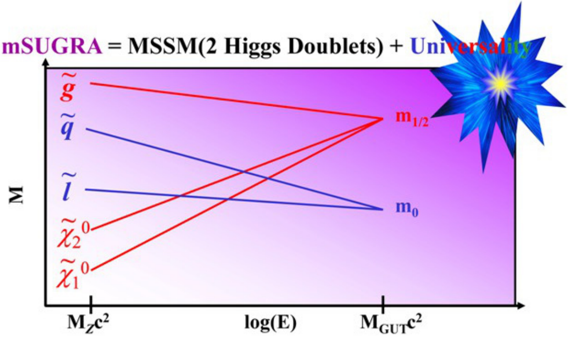
$$\Delta m_H(Q) \propto M_{\tilde{s}} \ln(Q)$$

- Fine tuning avoided if $M_{\tilde{s}} \lesssim 1\text{TeV}$.
- MSSM includes all soft breaking mass terms and interactions allowed by symmetry
- Gives $\sim$ 100 new free parameters.

- Hard to explore MSSM because of the large number of free parameters introduced by SUSY breaking
- Large parts of MSSM gives non-viable models (Flavour changing neutral currents, large CP violations . . .)
- Unification of SM couplings also suggests a simpler underlying theory at higher energy
- Consider simpler unified theory at high energy giving viable low energy theories (mSUGRA,. . .) or remove dangerous terms by hand (pMSSM)

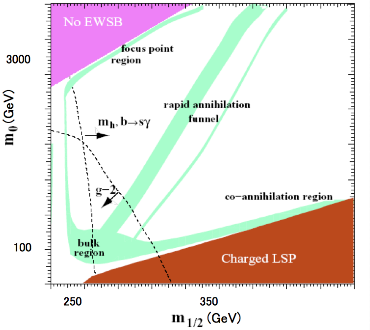
Model Name	Description	Parameters
pMSSM	MSSM with CP and R conservation	19 parameters
CMSSM / mSUGRA	Minimal supergravity model	$m_{1/2}$, m_0, tan β, A_0, sign (μ)
GMSB	Gravity Mediating Supersymmetry Breaking	Λ, M_{mess}, N_5, tan β, C_{grav}, sign (μ)
AMSB	Anomaly Mediated Supersymmetry breaking	$m_{3/2}$, m_0, tan β, sign (μ)

- mSUGRA assumes that all the MSSM parameters unify into only 5 parameters at the GUT scale
  - m_0: universal scalar mass
  - $m_{1/2}$: universal gaugino mass
  - A_0: universal sfermion-Higgs coupling
  - $\tan\beta$: ratio of vacuum expectation values of two Higgs doublets
  - sign(μ): sign of Higgsino mass parameter



- mSUGRA LSP: Lightest neutralino χ_1^0
- Dark Matter relic density is measured to be roughly $\Omega_{DM}h^2 \approx 0.11$
- Neutralino relic density generally orders of magnitude too large, only special regions with enhanced relic density reduction gives viable dark matter.

- **Bulk region:** LSP annihilation to fermion-antifermion pairs via sfermion exchange
- **Focus region:** Annihilation to WW, ZZ
- **Coannihilation region:** Small NLSP-LSP mass difference, typically $m_{\tilde{\tau}_1} \sim m_{\tilde{\chi}_0^1}$
- **Funnel region:** Decay to fermion pair through resonant A,H exchange, $2m_{\tilde{\chi}_0^1} \sim m_{A,H}$



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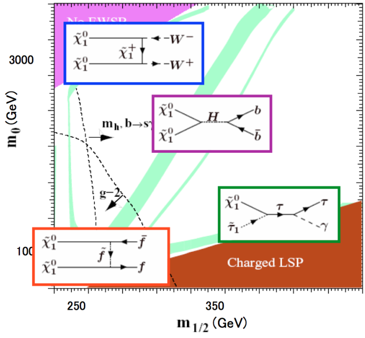
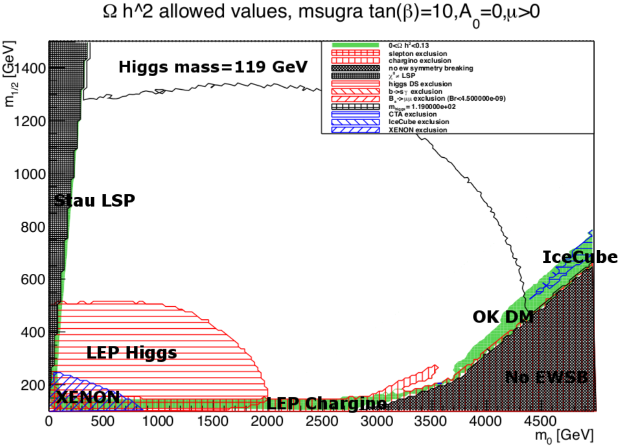


- In addition experimental constraints from sparticle masses, rare decays and $m_{h0} \sim 125$ GeV (see Knuts plot)



- Is mSUGRA excluded? If not what are the prospects of discovery at the LHC?

- Even in a very constrained version of SUSY such as mSUGRA the model space is large and complicted
- Traditional uniform searches cannot efficiently cover the whole space since it spends a lot of time sampling allready exclude regions
- A more efficient approach would be a guided random walk through the space according to a likelihood, related to how well the model fits certain requirements.
- We have implemented a method to efficiently search for potentially discoverable, non-excluded models.
- Method applied to search for mSUGRA models that can be probed using τ-leptons with 2012 LHC data

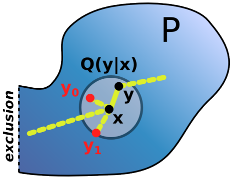
- To calculate the low energy properties of SUSY models we use several publicly available software packages

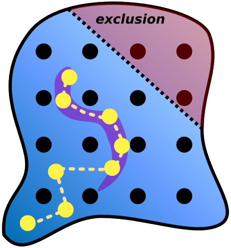
Table : software and outputs used for this work. Average values from `Pythia` are for final states with $|\eta| < 2.5$ and $p_T > 20\mathrm{GeV}$.

Tool	Used outputs
`ISAJET 7.81` & `isaRED`	SUSY masses, $\Gamma(B_s \to \mu\mu)$
`FeynHiggs 2.9.2` & `HiggsBounds 3.7.0`	Higgs sector
`darkSUSY 5.0.5`	$\Omega_\chi h^2$, $\Gamma(b \to s + \gamma)$
`Pythia 8.162`	σ_{LO},$\langle n, p_{T1}, p_{T2}\rangle$ for $\tau, e, \mu, \mathrm{jet}$,$\langle E_T^{\mathrm{miss}}\rangle$

- The output from these tools are used to construct model likelihoods used in the search

- To increase search efficiency we use Markov Chain Monte Carlo (MCMC)
- MCMC's employ Markov Chains and random walks to sample any distribution P
- Example: Metropolis-Hastings MCMC
  - Start at some point x and calculate $P(x)$
  - Sample new point y randomly from a proposal distribution $Q(y|x)$ (usually a Gaussian with mean x)
  - Calculate ratio $\alpha = \frac{P(y)Q(x|y)}{P(x)Q(y|x)}$
  - Compare α to random number $u \sim \mathcal{U}(0,1)$ and accept if $\alpha > u$, else stay and try new point
  - Continue process until some equilibrum criterion is met
- In this work $P(x)$ is constructed to favour non-excluded τ rich SUSY models, where $x = \{x_1, x_2, \ldots\}$ corresponds to a point in the SUSY parameter space



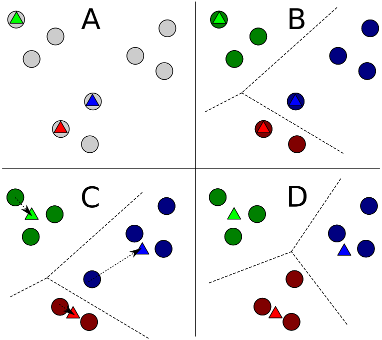


- Simplest MCMC has problems dealing with separated high likelihood regions of parameter space
- Tends to get stuck at local minimima, might take very long to move from one region to another.
- To deal with this problem we introduce the possibility of large jumps into the proposal distribution $Q(x|y)$
- This is done in the following way:
  1. Sample space uniformily to get an idea of where the interesting regions are
  2. Construct an approximation $Q_B(y)$ to the underlying distribution $P(y)$
  3. Let the full proposal $Q(x|y)$ be a combination of local $Q_L(y|x)$ and global $Q_B(y)$ proposals.

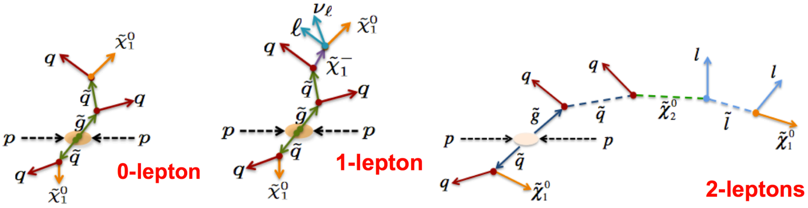
$$Q(y|x) = \alpha Q_L(y|x) + (1-\alpha) Q_B(y)$$

- The global term Q_B is constructed by fitting $P(x)$ to a mixture of Gaussians
- The local term at a point x $Q_L(y|x)$ is also gaussian with covariance proportional to that of the nearest component of the mixture.
- The approximation to $P(x)$ is improved as during sampling.
- The scale relating local and global covariances is also addapted to get a roughly optimal fraction of accepted local jumps $r_{acc} \sim 0.1$.
- To sample all different regions simultaneously we run multiple Markov chains in parallell, where we ensure that we have a good spread in starting points.

- From the samples obtained by the search we construct reference models, to be used for optimizing experimental searches.
- This is done using a clustering algorithm (g-means) where the number of clusters are determined automatically



- Coannihilation region reduces relic density but also gives and increase in χ_2^0 branching fraction to $\tilde{\tau}\tau$
- looking for τ's important
- Also UiB involved in SUSY searches with τ-final states
- Signatures of SUSY are jets, missing transverse energy $\not{E}_T$, and possibly leptons



- We are interested in models which agree with experimental constraints and produce observable tau's at LHC in 2012.
- We construct the likelihood P to explore SUSY space by defining an experimental likelihood P_{exp}, and a "discoverability" likelihood P_τ

$$P_{\mathrm{tot}} = P_{\mathrm{exp}} \cdot P_\tau$$

- The discoverability likelihood for a given model is related to the probability of producing one or more τ-events at LHC in 2012, while the table lists the experimental constraints used for P_{exp}.

Constraints	**Likelihoods $\mathbf{P_i}$**	**Values**
$\tilde{\chi}_1^0$ LSP, Correct EWSB, No tachyons ...	OK: 1 Not OK: 0	ISAJET 7.81
Sparticle masses, $\Delta\rho$, Z-width	OK: 1 Not OK: 0	darkSUSY 5.0.5
OK Higgs sector	OK: 1 Not OK: 0	HiggsBounds 3.7.0
Branching fraction $B_s \to \mu\mu$	OK: 1 Not OK: 0	$\Gamma(B_s \to \mu\mu) < 4.5 \cdot 10^{-9}$
Relic density Ωh^2	$\exp\left[\frac{(\Omega h^2 - \min(\Omega h^2, \mu_\Omega))^2}{-2\sigma_\Omega^2}\right]$	$[\mu_\Omega, \sigma_\Omega] = [0.1126, 0.0036]$
Branching fraction $b \to s + \gamma$	$\exp\left[\frac{(\Gamma_{\mathrm{bsg}} - \mu_{\mathrm{bsg}})^2}{-2\sigma_{\mathrm{bsg}}^2}\right]$	$[\mu_{\mathrm{bsg}}, \sigma_{\mathrm{bsg}}] = [3.55, 0.33] \cdot 10^{-4}$
Higgs mass m_{h0}	$\exp\left[\frac{(m_{h0} - \mu_{h0})^2}{-2\sigma_{h0}^2}\right]$	$[\mu_{h0}, \sigma_{h0}] = [125, 1]$ GeV

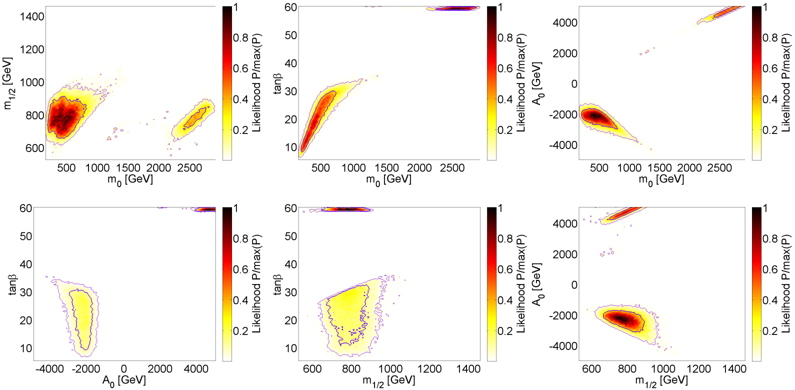
- We use experimental and theoretical constraints to restrict the search range
- Theoretical restrictions require $\tan\beta < 60$ and naturalness requires $m_0, m_{1/2} \sim TeV$, while experimental bounds from LEP require $\tan\beta > 2$, $m_0, m_{1/2} > 60\mathrm{GeV}$.
- For simplicity search is restricted to positive values of signμ, preferred by experiments
- A_0 is chosen to lie between $-5000\mathrm{GeV}$ and $5000\mathrm{GeV}$

Parameter	Range
m_0	[60,3000] GeV
$m_{1/2}$	[60,3000] GeV
A_0	[-5000,5000] GeV
$\tan\beta$	[2,60]
sign(μ)	$+1$

- The results presented here comes from a run on 20 cpu's run for a 100 hours resulting in a sample size of 254295 models.
- Two distinct regions found, both with sfermion masses $\tilde{m}_{1/2} \in [500, 1000]$ GeV to give sufficient cross section.
  1. Region A$\sim$ 80%: $A_0 \in [-4000, -2000]\mathrm{GeV}, \tan\beta \in [10, 40] m_0 \in [500, 1000]\mathrm{GeV}$
  2. Region B$\sim$ 20%: $A_0 \sim [2000, 4000]\mathrm{GeV}, \tan\beta \sim 60, m_0 \in [2000, 3000]\mathrm{GeV}$

m_0 [GeV]	$m_{1/2}$ [GeV]	A_0 [GeV]	$\tan\beta$	$\ln P$	Ωh^2	m_{h0} [GeV]	N_τ
2233	669.4	4067	58.73	$-9.872 \cdot 10^{-5}$	0.1129	125.0	53.04
598.1	704.0	-2287	26.79	$-1.825 \cdot 10^{-2}$	0.1136	124.6	20.29

Likelihood distributions

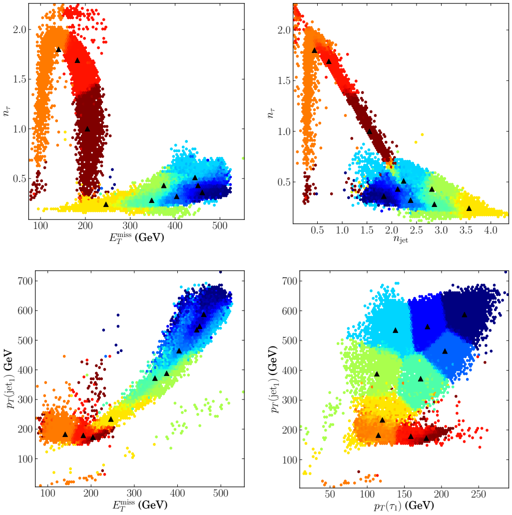


- The models are clustered according to phenomenological parameters

$$\{\not{E}_T, n_{\text{jet}}, p_T(\text{jet}_1), n_\tau, p_T(\tau_1)\}$$

- 10 are found clusters found

id	n	$\not{E}_T$ [GeV] min	$\not{E}_T$ [GeV] cent	$\not{E}_T$ [GeV] max	n_{jet} min	n_{jet} cent	n_{jet} max	$\text{jet}_1(p_T)$ [GeV] min	$\text{jet}_1(p_T)$ [GeV] cent	$\text{jet}_1(p_T)$ [GeV] max	n_τ min	n_τ cent	n_τ max	$\tau_1(p_T)$ [GeV] min	$\tau_1(p_T)$ [GeV] cent	$\tau_1(p_T)$ [GeV] max
1	4609	229.2	**460.5**	522.5	0.5	**1.8**	2.5	460.0	**587.4**	730.3	0.3	**0.4**	0.6	200.3	**230.9**	289.1
2	3374	370.0	**451.1**	522.8	1.6	**2.1**	2.7	448.9	**547.0**	659.1	0.2	**0.4**	0.7	155.9	**181.1**	208.2
3	5451	234.7	**403.5**	467.3	1.2	**2.4**	2.9	360.5	**464.7**	555.3	0.2	**0.3**	0.5	173.9	**204.6**	250.1
4	4860	365.9	**444.4**	524.1	1.1	**2.2**	2.9	431.6	**534.9**	693.7	0.2	**0.5**	0.9	74.1	**138.0**	163.9
5	3414	219.2	**347.8**	425.7	2.0	**2.9**	3.5	253.5	**371.9**	482.6	0.2	**0.3**	0.5	141.5	**171.9**	215.3
6	1900	193.1	**374.8**	552.0	1.3	**2.8**	3.5	138.2	**388.2**	505.5	0.1	**0.4**	0.8	10.6	**113.0**	147.3
7	1635	96.8	**245.9**	350.1	2.1	**3.6**	4.3	50.4	**233.7**	345.8	0.1	**0.2**	1.0	14.3	**120.4**	169.2
8	5574	73.5	**140.2**	219.5	0.0	**0.4**	1.4	9.3	**182.4**	444.7	0.3	**1.8**	2.2	39.4	**115.0**	151.6
9	5069	150.7	**182.1**	247.8	0.0	**0.7**	1.3	48.3	**178.8**	446.2	1.2	**1.7**	2.2	114.1	**158.7**	262.2
10	2283	78.6	**204.4**	254.8	0.2	**1.6**	2.5	57.5	**172.6**	432.2	0.3	**1.0**	1.5	89.4	**179.6**	259.7


n_τ
$E_T^{\rm miss}$ (GeV)
n_τ
$n_{\rm jet}$
$p_T({\rm jet}_1)$ GeV
$E_T^{\rm miss}$ (GeV)
$p_T({\rm jet}_1)$ (GeV)
$p_T(\tau_1)$ (GeV)

- the centroid (mean) of ech cluster is chosen as a reference points

id	m_0 [GeV]	$m_{1/2}$ [GeV]	A_0 [GeV]	$\tan\beta$ [GeV]	$\langle N_\tau \rangle$	$\ln P$	Ωh^2	mh_0 [GeV]	σ [fb]
1	409.0	675.0	-1665.1	22.9	27.3	-0.5	0.1	123.3	10.2
2	324.9	622.6	-1444.7	20.0	65.6	-0.6	0.1	122.7	20.3
3	553.0	727.4	-2346.2	24.0	16.2	-0.1	0.1	124.6	6.8
4	306.1	802.3	-2074.4	12.9	11.4	-0.6	0.1	124.0	3.0
5	446.5	674.6	-2259.8	20.0	37.8	-0.3	0.1	123.9	18.0
6	352.7	733.3	-2239.0	15.1	16.6	-0.4	0.1	124.2	5.2
7	578.5	724.0	-2671.8	22.7	34.0	-1.3	0.1	122.7	18.9
8	2528.2	805.9	4633.1	58.6	15.3	-0.2	0.1	123.8	1.1
9	2482.0	739.2	4433.1	58.8	25.0	-0.3	0.1	124.8	2.0
10	2296.7	721.6	4051.4	58.5	16.9	-5.5	0.1	121.5	2.2

- We have found two distinct regions of mSUGRA parameterspace which are not excluded by current experiments and will likeli produce observable events at LHC in 2012
- However most of the models will give roughly around 50 events, while ruff estimates suggests more than 300 events is neccesary for discovery $\rightarrow$ Need more data!
- 10 reference points also produced to cover the phenomeological range of the sample

- Look at other parameter spaces such as GMSB, pMSSM etc
- Incorporate astrophysical constraints (More on these in Knuts talk)
- Include detector simulations and more proper statistical analysis of simulated data
- Approximate experimental sensitivity $\rightarrow$ more consistent phenomenological clustering
- This work will be part of the new ATLAS Astro Forum as one of the approved topics for first analyses