Implications of LHC Searches on Constrained Supersymmetric Models

Matthew Dolan

IPPP
University of Durham

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What's a SUSY?

Bosons $\Leftrightarrow$ Fermions

- $\mathcal{Q}|\text{Fermion}\rangle = |\text{Boson}\rangle$
  $\mathcal{Q}|\text{Boson}\rangle = |\text{Fermion}\rangle$
- $\mathcal{Q}|\text{top}, t\rangle = |\text{scalar top}, \tilde{t}\rangle$
  $\mathcal{Q}|\text{gluon}, g\rangle = |\text{gluino}, \tilde{g}\rangle$
- Doubles size of SM spectrum.

Breaking SUSY

- Unbroken SUSY: All particles in multiplet have same mass.
- Reality: $m_e \neq m_{\tilde{e}} \implies$ SUSY broken.

Why?

SUSY can

Stabilise electroweak hierarchy.

Unification of gauge couplings.

Radiative electroweak symmetry breaking.

Cold dark matter candidate: neutralino,gravitino...

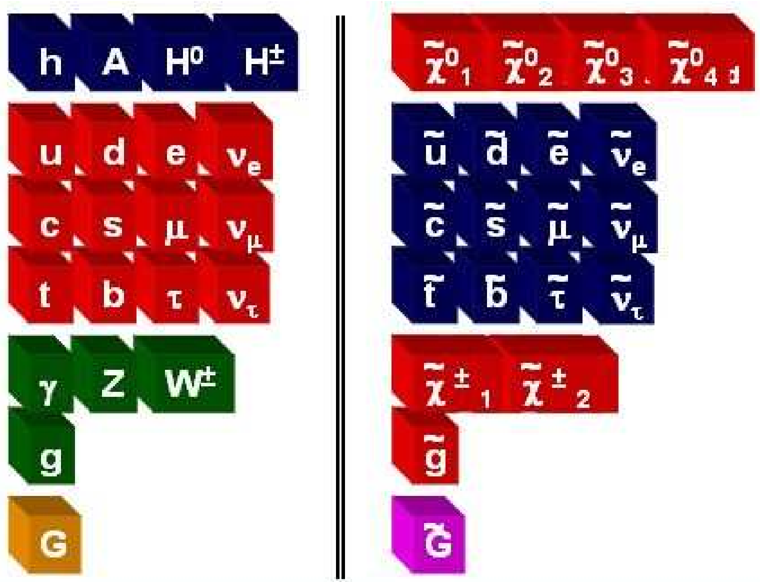
The MSSM

- Take the field content of the SM and promote all fields to superfields. Adds superpartners differing by $s = 1/2$.
- SUSY partners should have masses $\sim$ 0.1–1 TeV.

The Higgs Sector

- Superpartner of Higgs boson is a fermion $\implies$ anomalies don't cancel anymore.
- Solution: Add extra Higgs doublet.
- Physical states: $h^0, H^0, A, H^{\pm}$ and Goldstone bosons: G^0, $G^{\pm}$
- $\tan\beta = v_2/v_1$

The Minimal Supersymmetric Standard Model

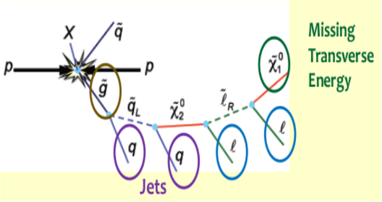


Desperately Seeking SUSY

SUSY events typically involve

Missing energy $\not{E}_T$ and one or more of the following:

- Jet production
- Leptons



ATLAS Jets+MET Search (1/fb)

Signal Region	$\geq$ 2-jet	$\geq$ 3-jet	$\geq$ 4-jet	High mass
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 130	> 130	> 130	> 130
Leading jet p_{T}	> 130	> 130	> 130	> 130
Second jet p_{T}	> 40	> 40	> 40	> 80
Third jet p_{T}	–	> 40	> 40	> 80
Fourth jet p_{T}	–	–	> 40	> 80
$\Delta\phi(\mathrm{jet}, P_T^{\mathrm{miss}})_{\mathrm{min}}$	> 0.4	> 0.4	> 0.4	> 0.4
$E_{\mathrm{T}}^{\mathrm{miss}}/m_{\mathrm{eff}}$	> 0.3	> 0.25	> 0.25	> 0.2
m_{eff}	> 1000	> 1000	$> 500/1000$	> 1100

The CMSSM and a simplified model

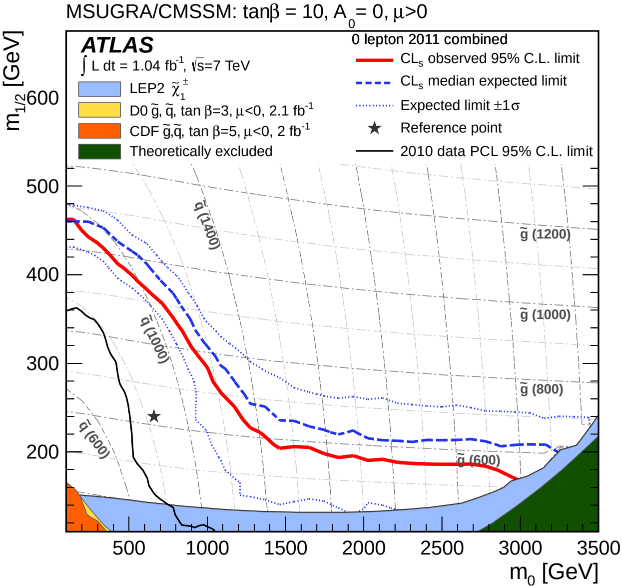
CMSSM: A 4 parameter model

- m_0: Universal scalar masses
- $m_{1/2}$: Universal gaugino masses
- A_0: Universal trilinear couplings
- $\tan\beta$
- All defined at $M_{GUT} \approx 2 \times 10^{16}$ GeV

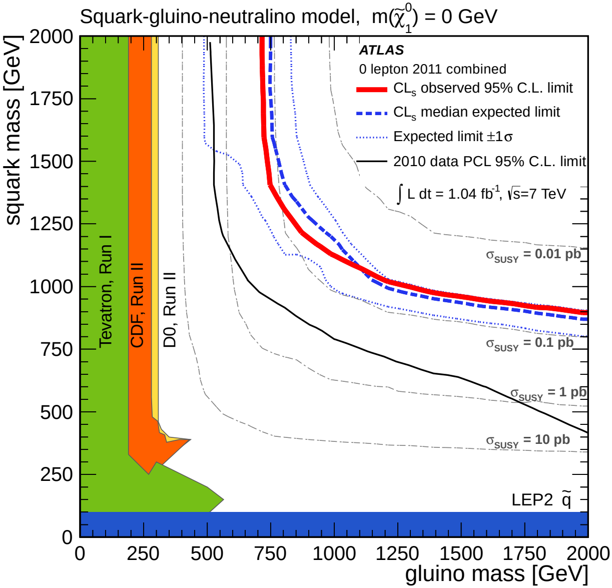
A simplified model

- m_{squark} and m_{gluino}
- Massless neutralino.

ATLAS Jets+MET in CMSSM



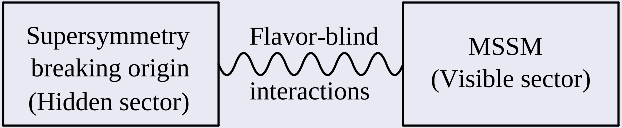
ATLAS Jets+MET in a simplified model.



What about other models?

Gauge Mediation

- SUSY broken in hidden sector
- SUSY breaking is mediated to MSSM by a messenger sector using gauge interactions



- Preserve unification: messengers in $5 \oplus \bar{5}$ of $SU(5)$.

General Gauge Mediation

Split Gauge Mediation

- Have messengers (q, l) in $5 \oplus \bar{5}$ with messenger couplings

$$\lambda_l X l \bar{l} + \lambda_q X q \bar{q}$$

- Get gaugino masses (at messenger scale)

$$m_{\tilde{g}} = \frac{\alpha_3}{4\pi}\Lambda_T \quad m_{\tilde{w}} = \frac{\alpha_2}{4\pi}\Lambda_D \quad m_{\tilde{b}} = \frac{\alpha_1}{4\pi}(\frac{2}{3}\Lambda_T + \Lambda_D)$$

- Scalar masses

$$m_{\tilde{f}}^2 = 2\left(C_3(\frac{\alpha_3}{4\pi})^2\Lambda_T^2 + C_2(\frac{\alpha_2}{4\pi})^2\Lambda_D^2 + \frac{Y^2}{2}(\frac{\alpha_1}{4\pi})^2(\frac{2}{3}\Lambda_T^2 + \Lambda_D^2)\right.$$

General Gauge Mediation

Another possibility

- Have gaugino masses

$$m_{\tilde{\lambda}_i} = \frac{k_i \alpha_i}{4\pi} \Lambda_G$$

- And scalar masses

$$m_{\tilde{f}}^2 = 2 \sum_{i=1}^{3} C_i k_i \frac{\alpha_i^2}{(4\pi)^2} \Lambda_S^2$$

What are limits like in these kinds of theories?

Re-interpreting SUSY searches

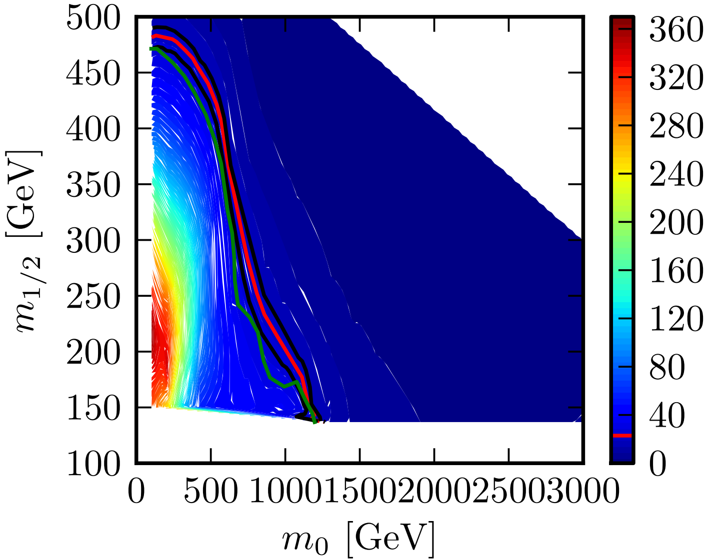
Strategy

- Generate grids of points in desired models (Softsusy)
- Write analysis code in Rivet framework (generator independent)
- LO cross-section and signal-only event generation by Herwig++
- NLO K-factors from PROSPINO.

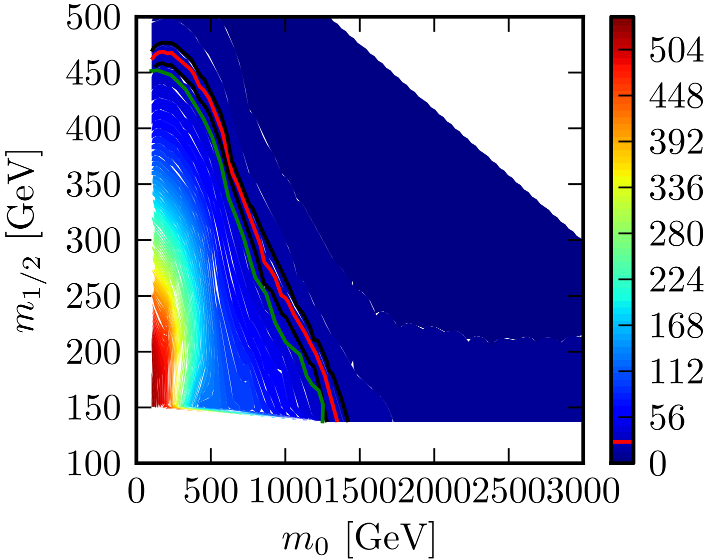
Validation

- Need to validate our code against the ATLAS results.

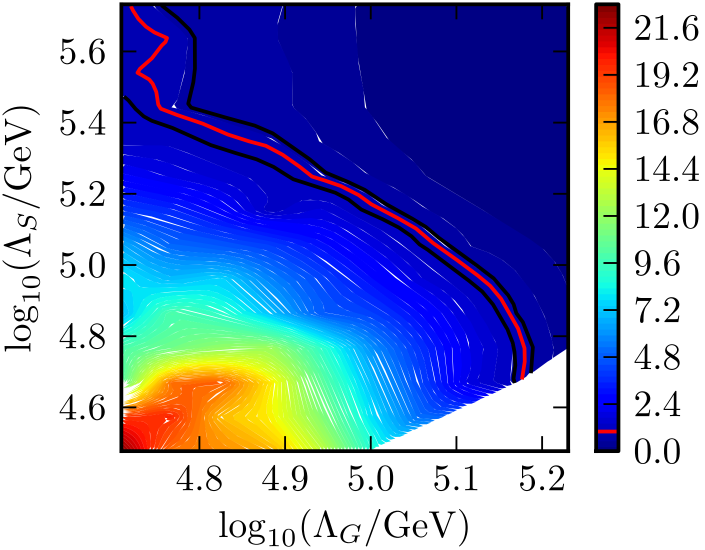
Validation: 2j channel



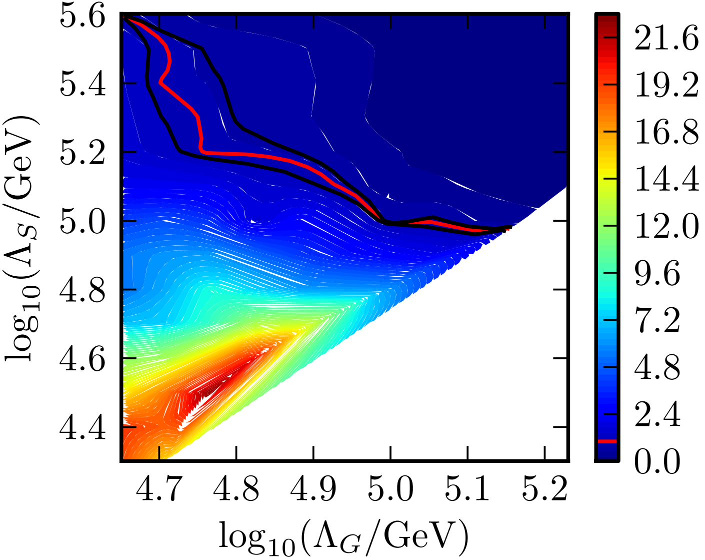
Validation: 3j channel



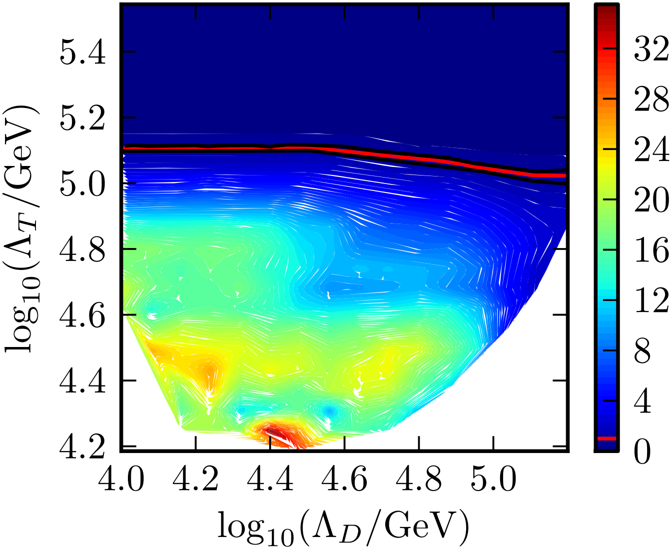
GGM: $M_{mess} = 10^{14}$ GeV, $\tan\beta = 5$



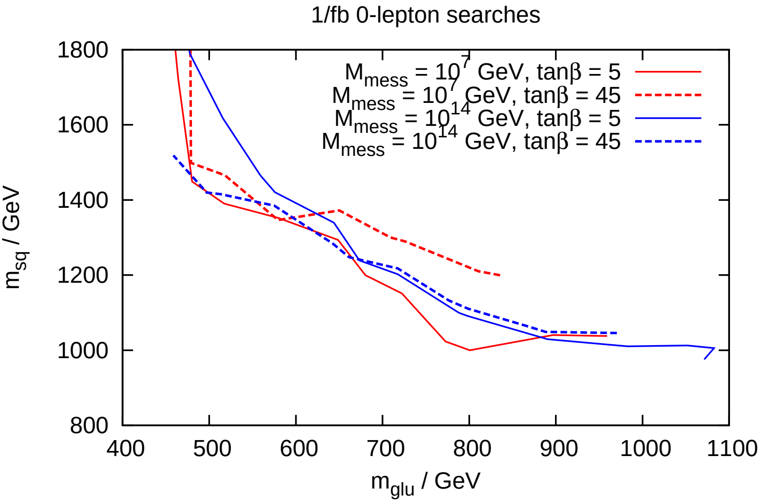
GGM: $M_{mess} = 10^7$ GeV, $\tan\beta = 5$



Split GGM


5.4
5.2
5.0
4.8
4.6
4.4
4.2
$\log_{10}(\Lambda_T/\mathrm{GeV})$
4.0
4.2
4.4
4.6
4.8
5.0
$\log_{10}(\Lambda_D/\mathrm{GeV})$
32
28
24
20
16
12
8
4
0

All Together Now



Mass Limits

For $m_{\tilde{q}} = m_{\tilde{g}}$

- Compressed spectrum: 600 GeV
- AMSB: 900 GeV
- CMSSM: 950 GeV
- PGGM7: 960 GeV
- PGGM14: 1 TeV
- Simplified Model: 1075 GeV

Split GGM

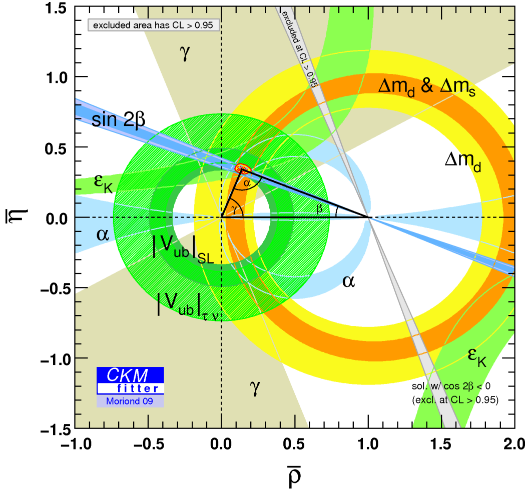
- Automatically have $m_{\tilde{g}} \sim m_{\tilde{q}}$, both controlled by Λ_T
- Limit varies from $m_{\tilde{g}} \sim 950$ GeV down to $m_{\tilde{g}} \sim 800$ GeV, depending on Λ_D

Global Fits

Confronting a Model with Data

- Combine measurements
- Compare with predictions
- Constrain parameters
- Exclude model?

A well-known global fit



The Models

CMSSM: 4 parameters

- The usual story: $m_0, m_{1/2}, A_0$ and $\tan\beta$

NUHM1: 5 parameters

- As in CMSSM, but Higgs masses become an independent parameter
- $m_{H_u}^2 = m_{H_d}^2 \neq m_0^2$
- Equivalent to M_A free parameter at EW scale.

Constraints on SUSY

Low Energy Precision Data

Flavour physics: $BR(B \to X_s\gamma)$, $B \to \tau\nu$, $B_s \to \mu^+\mu^-$. Also $(g-2)_\mu$

High Energy Precision Data

Precision electroweak observables: M_W

Cosmology/Astrophysics

Relic density: $\Omega_{DM}h^2 = 0.1109 \pm 0.0056$ (WMAP7)
DM direct detection: CDMS, XENON...

Direct Searches

ATLAS, CMS, LEP, Tevatron

Observables

Low Energy Obs	Electroweak Observable
$BR(B \to X_s\gamma)$	m_W
$BR(B_s \to ll)$	$\sin^2\theta^l_{eff}$
$BR(B_d \to ll)$	$A^{0,b}_{fb}$
$R_{\Delta M_s}$	$A^{0,c}_{fb}$
$R_{B\tau\nu}$	R^0_l
$R(B \to X_s ll)$	σ^0_{had}
$R(K \to \pi\nu\bar{\nu})$	$\Delta\alpha^{(0)}_{had}(m_Z^2)$
$BR(K \to \tau\nu)$	$\mathcal{A}_c$
$R_{\Delta M_K}$	$A^0_{LR}(SLD)$
	R^0_b
$(g-2)_\mu$	R^0_c
	m_t
m_h	m_Z
$\Omega_{\rm DM}h^2$	$\mathcal{A}_b$

Fit Methods

Statistical Measure

$\chi^2_{tot} = \sum_{obs} \chi^2_i = \sum_{obs} \frac{(C_i^2 - P_i^2)}{\sigma_i^2}$

- For derived quantities σ_i incorporates both experimental and theoretical errors.

Fit Method

- Use Markov Chain Monte Carlo for sampling, with χ^2 minimisation using `Minuit` as an 'afterburner'.
- Sample $\mathcal{O}(10^8)$ points for CMSSM/NUHM

Best-fit Points (before LHC data)

Model	Min χ^2	Prob	$m_{1/2}$	m_0	A_0	$\tan\beta$
CMSSM	21.5	37%	360	90	400	15
NUHM1	20.8	29%	340	110	-520	13

Comments

- CMSSM/NUHM: Preference for light SUSY, with $m_{\tilde{q}} \sim m_{\tilde{g}} \approx 600 - 700$ GeV
- Small $\tan\beta$, with $\tilde{\tau}$ co-annihilation.

Incorporating LHC Data

SUSY Searches

- In CMSSM/NUHM 0-lepton searches provide the maximum reach.
- 0l searches independent of $\tan\beta$ and A_0.
- We consider both the ATLAS 0l and CMS α_T searches.
- Other searches are not as strong as these in the CMSSM.

Method

- Pick the search with the highest *expected* sensitivity along rays in m_0-$m_{1/2}$ plane.

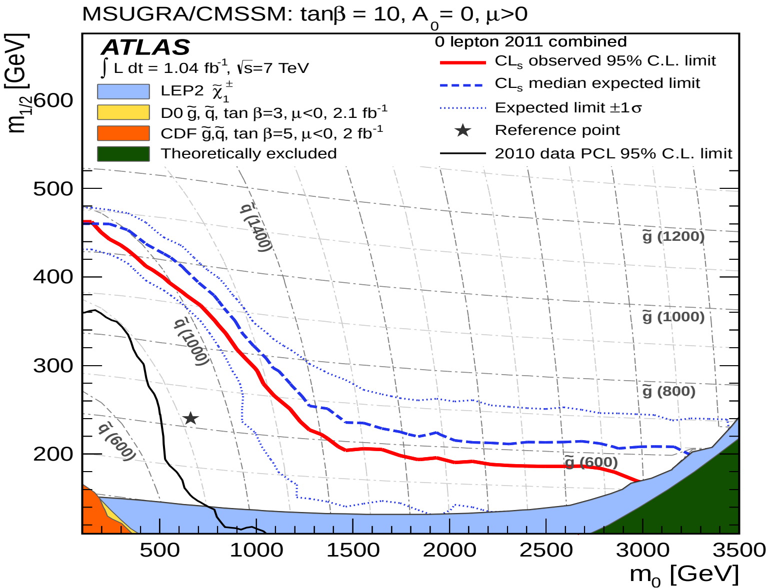
Calculating χ^2: Jets + MET

Method

- Pick the search with the highest *expected* sensitivity along rays in m_0-$m_{1/2}$ plane.

- Use $n_{events} \propto M^{-4} (M^2 \equiv m_0^2 + m_{1/2}^2)$
- Then $\chi^2 \sim \chi^2_{95\%} \left(\frac{M_p}{M_{95\%}} \right)^{-4}$
- Reproduces shape of contour in region of interest.

ATLAS Jets + MET search



$BR(B_s \to \mu^+\mu^-)$

This branching ratio gets SUSY corrections proportional to $\tan^6 \beta$.

Searches

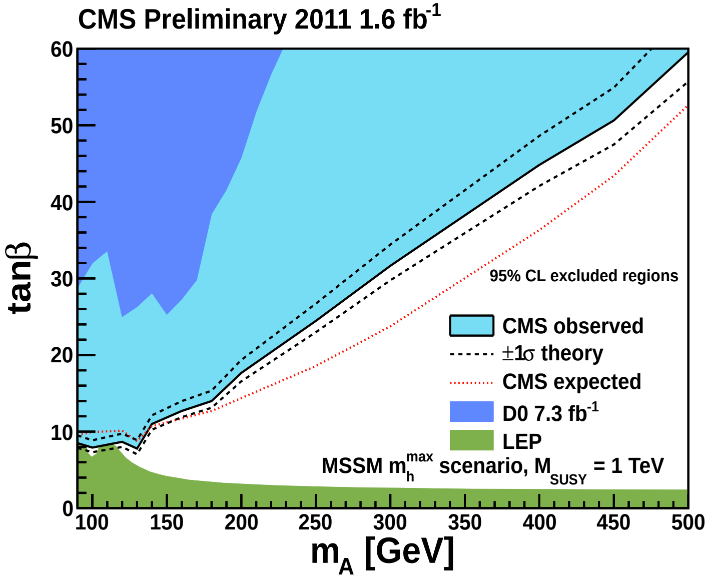
- Upper bounds set by LHCb and CMS with $1 fb^{-1}$
- Likelihood function from LHCb-CMS combination
- Yields $BR(B_s \to \mu^+\mu^- -) < 1.08 \times 10^{-8}$ ($\sim$ 3xSM) at 95% CL, with minimum near SM value.
- CDF claim two-sided limit - (unofficial) combination discussed in paper.

Heavy Higgs Searches

$H/A \to \tau\tau$

- CMS search with $1.6 fb^{-1}$, only affects NUHM1
- CMS provide 68, 95 and 99.7% CL contours
- Calculate $\sigma \times BR$ using $\sigma(bb \to H_{SM})$, and correct with effective NUHM1 couplings from FeynHiggs.

CMS $H/A \to \tau\tau$ limit

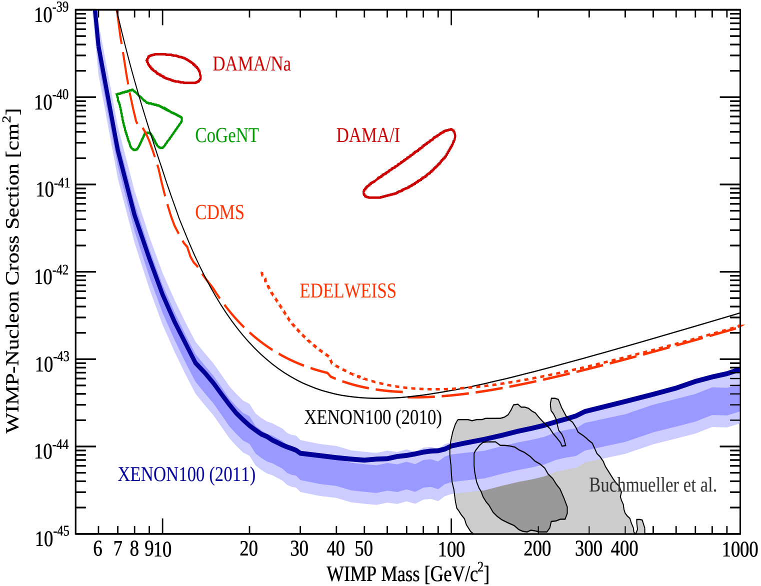


Dark Matter Direct Detection

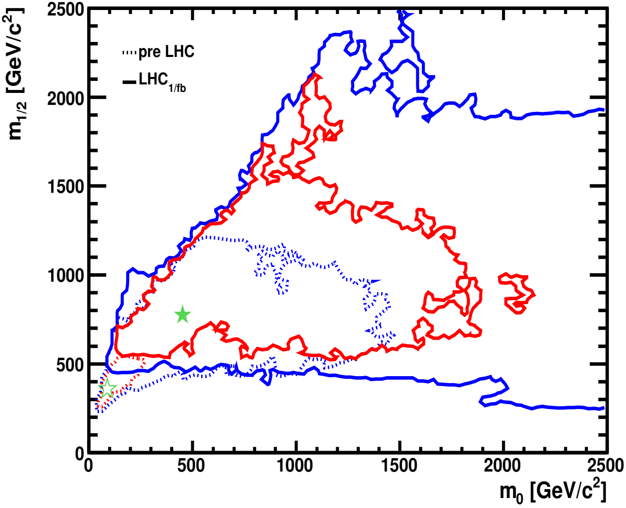
XENON100

- Observed 3 events, expected 1.8 ± 0.6
- Construct likelihood model for event numbers using CL_S & Poisson statistics.
- 90% CL corresponds to 6.1 events, and rescale from contour using calculated σ_p^{SI}.
- Slight excess leads to $\chi^2 \sim 0.3$ for small σ_p^{SI}

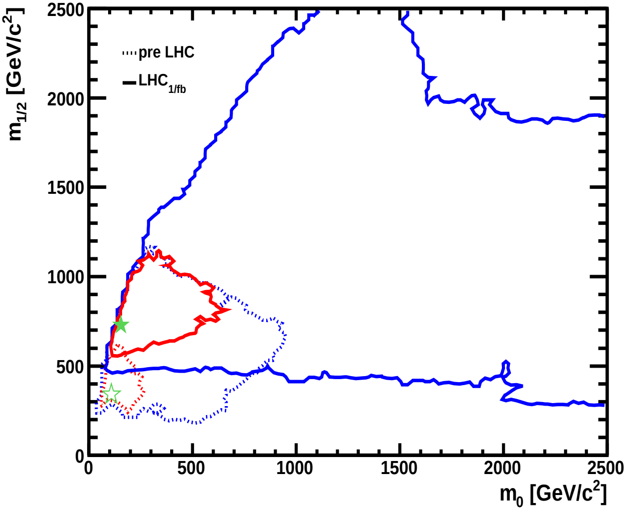
XENON100 Results



CMSSM m_0–$m_{1/2}$



NUHM m_0–$m_{1/2}$


pre LHC
LHC1/fb
2500
2000
1500
1000
500
0
$m_{1/2}$ [GeV/c^2]
0
500
1000
1500
2000
2500
m_0 [GeV/c^2]

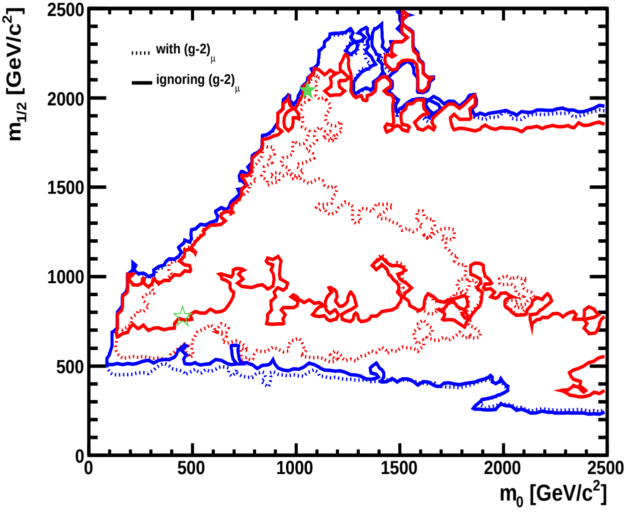
Best-fit points: CMSSM

Model	χ^2/d.o.f.	Prob	$m_{1/2}$	m_0	A_0	$\tan\beta$
pre-LHC	21.5/20	37%	360	90	400	15
$\mathrm{LHC}_{1/fb}$	28.8/22	15%	780	450	1100	41
No $(g-2)_\mu$	21.3/20	43%	2000	1050	430	22

Comments

- P-value assumes sum of normal distributions - fully frequentist thing would be to throw toys.
- P-value drops dramatically after 1/fb
- Driven by tension with $(g-2)_\mu$ - omit this and no tension.

CMSSM omitting $(g-2)_\mu$



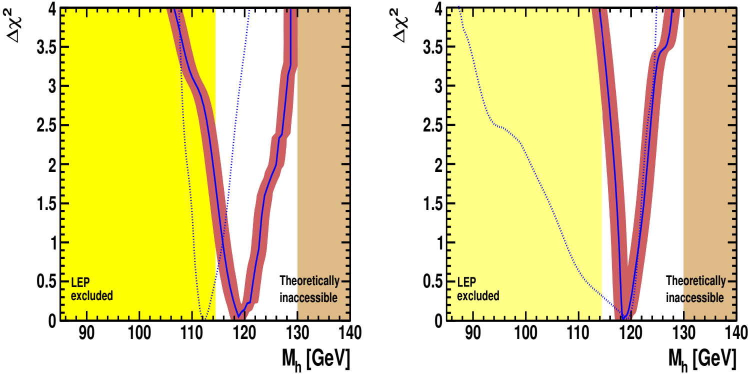
Best-fit points: NUHM1

Model	χ^2/d.o.f.	Prob	$m_{1/2}$	m_0	A_0	$\tan\beta$
NUHM1	20.8/18	29%	340	110	-520	13
$\mathrm{LHC}_{1/fb}$	27.3/21	16%	730	150	910	41
No $(g-2)_\mu$	20.3	43%	2020	1410	-2580	48

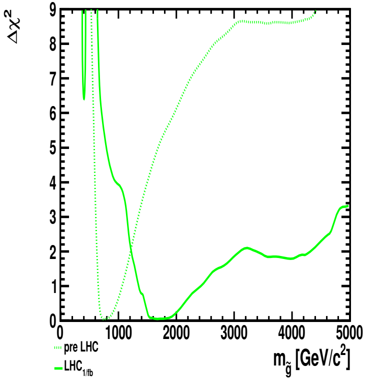
Comments

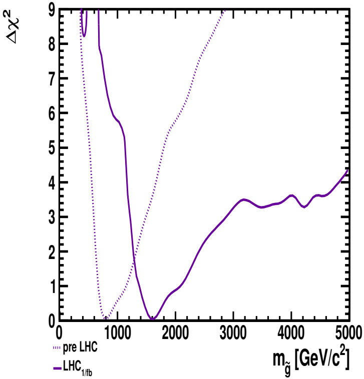
- Again, drop by factor ~ 2 in p-value.
- $\tan\beta$ increases by ≈ 30.

m_h: Predicted by omitting LEP constraint

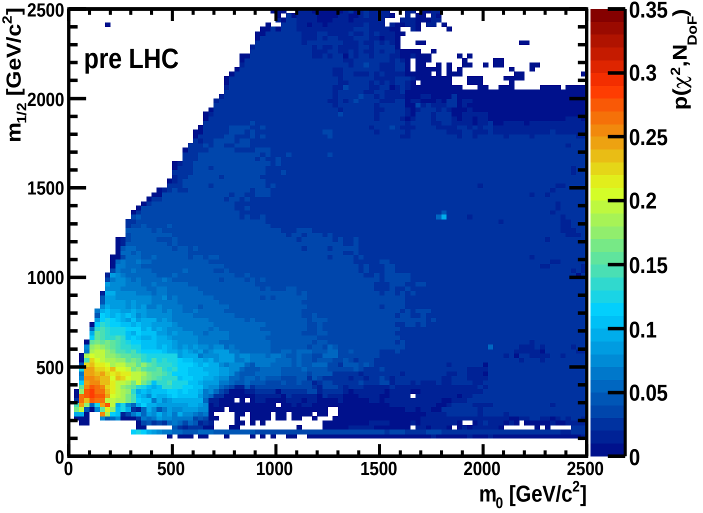


Gluino mass $m_{\tilde{g}}$

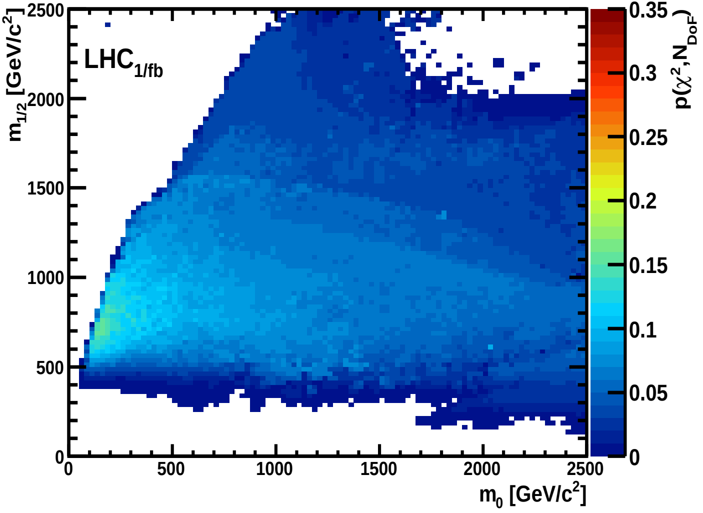




P values: NUHM1 pre LHC



P values: NUHM1 post LHC



The F-test

Can we compare the MSSM and SM?

- Want to compare two models, A and B say, where B is a supermodel of A.
- Does the data justify going from model A to model B?
- If model A is correct/sufficient, expect that relative increase in χ^2 going from A to B is equal to relative increase in degrees of freedom:

$$\frac{\chi_A^2 - \chi_B^2}{\chi_B^2} \approx \frac{A_{d.o.f} - B_{d.o.f.}}{B_{d.o.f.}}$$

The F-test

Can we compare the MSSM and SM?

- If B correct, expect relative increase of χ^2 greater than relative increase in d.o.f.

$$\frac{\chi_A^2 - \chi_B^2}{\chi_B^2} > \frac{A_{d.o.f} - B_{d.o.f.}}{B_{d.o.f.}}$$

$$F_\chi \equiv \frac{(\chi_A^2 - \chi_B^2)/(A_{d.o.f} - B_{d.o.f.})}{\chi_B^2/B_{d.o.f.}}$$

If $F_\chi > 1$

- Model B is better than A.
- Coincidence - calculate a p-value.

SM vs MSSM

Apples and Oranges

- Including DM: CMSSM/NUHM always wins.
- So consider ’everything else’ and omit DM.
- SM can’t explain $(g-2)_\mu$, but no tension with jets+MET search.
- Get $p_{SM} \approx 9\%$ with $(g-2)_\mu$, $p_{SM} \approx 49\%$ without.
- Probability switching to CMSSM is warranted: 90%, NUHM1: 97%.
- Omit $(g-2)_\mu$: no point switching from SM.

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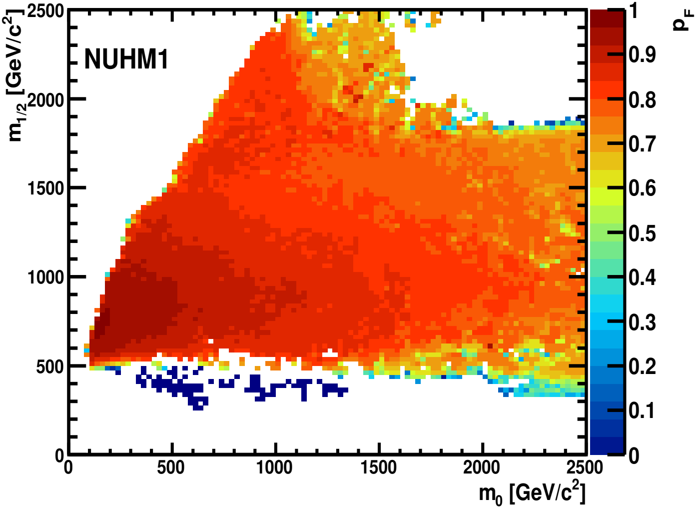
F-test: NUHM1


NUHM1
$m_{1/2}$ [GeV/c^2]
m_0 [GeV/c^2]
p_F
0
500
1000
1500
2000
2500
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

Summary

Limits

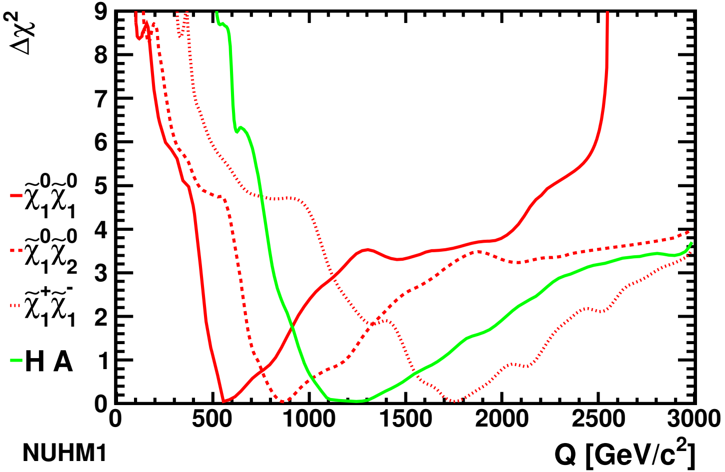
- Compressed spectra $m_{\tilde{q}} \approx m_{\tilde{g}} \approx 600$ GeV
- Limits on $m_{\tilde{q}} \approx m_{\tilde{g}} \approx 900$ GeV in some simple models.
- Limits significantly overstated for simplified models.

Fits

- CMSSM increasingly unlikely
- NUHM1 better fit.
- Decouple strong and weakly interacting sectors?
- Effect of Higgs mass measurement?

Bonus Slides

e^+e^- pair production thresholds (NUHM1)



e^+e^- pair production thresholds (NUHM1)