BBC Mobile

News | Sport | Weather | Travel | TV

NEWS SCIENCE & ENVIRONMENT

Home | UK | Africa | Asia-Pac | Europe | Latin America | Mid-East | South Asia | US & Canada | Business

27 August 2011 Last updated at 06:41 GMT

LHC results put supersymmetry theory 'on the spot'

… nevertheless

Supersymmetry after 1/fb of LHC Data

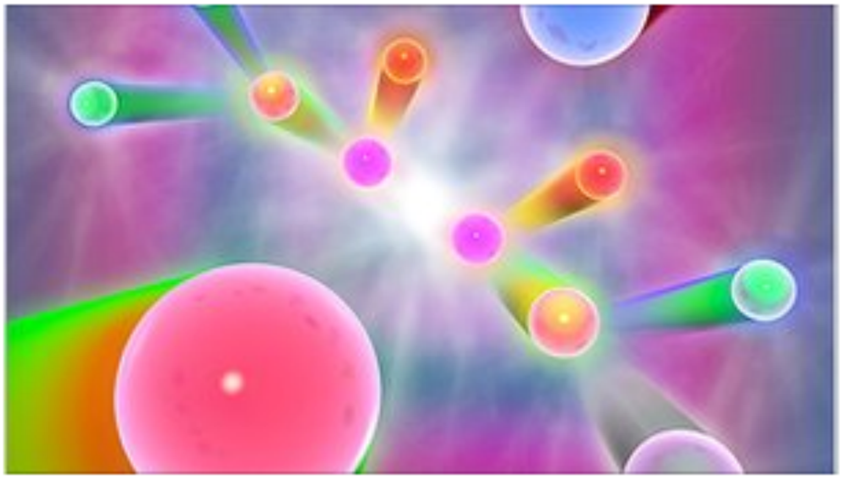
Results from the Large Hadron Collider (LHC) have all but killed the simplest version of an enticing theory of sub-atomic physics.

John ELLIS,

Kings College London

& CERN, Geneva, Switzerland

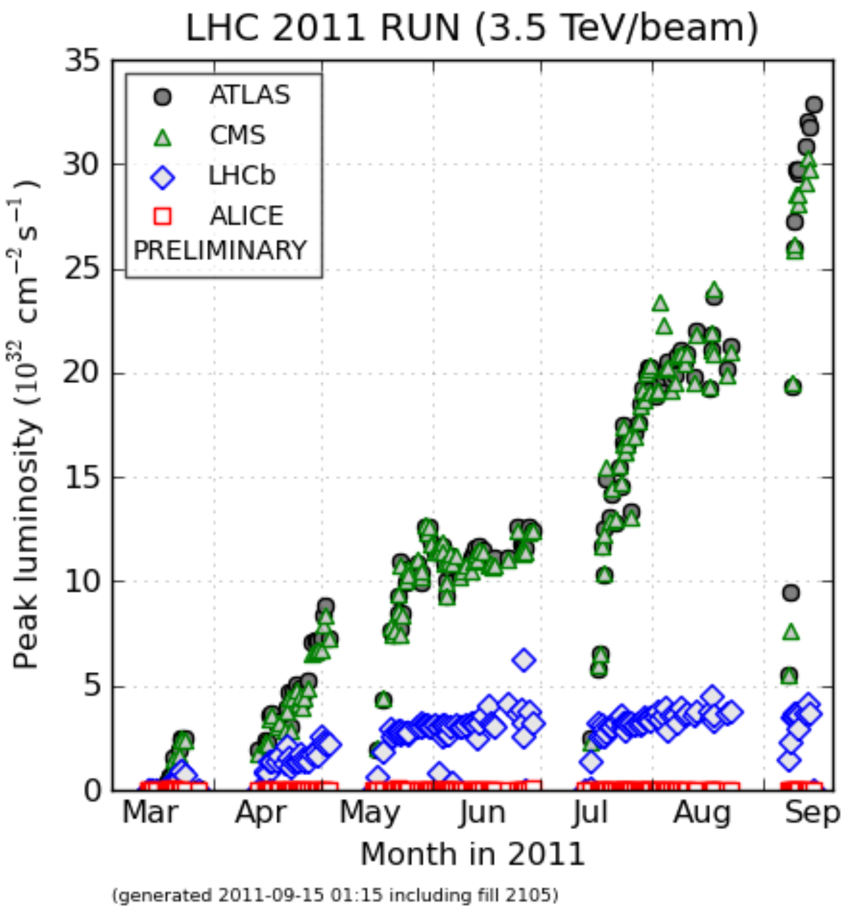
Theorists working in the field have told BBC



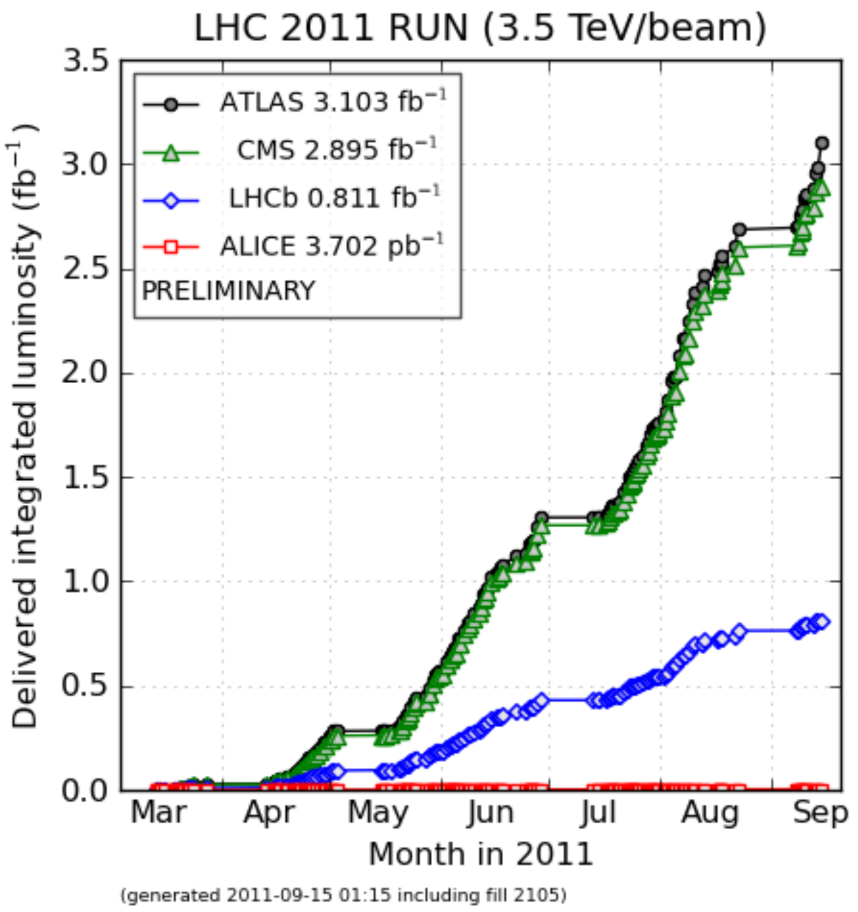
Supersymmetry predicts the existence of mysterious super particles.

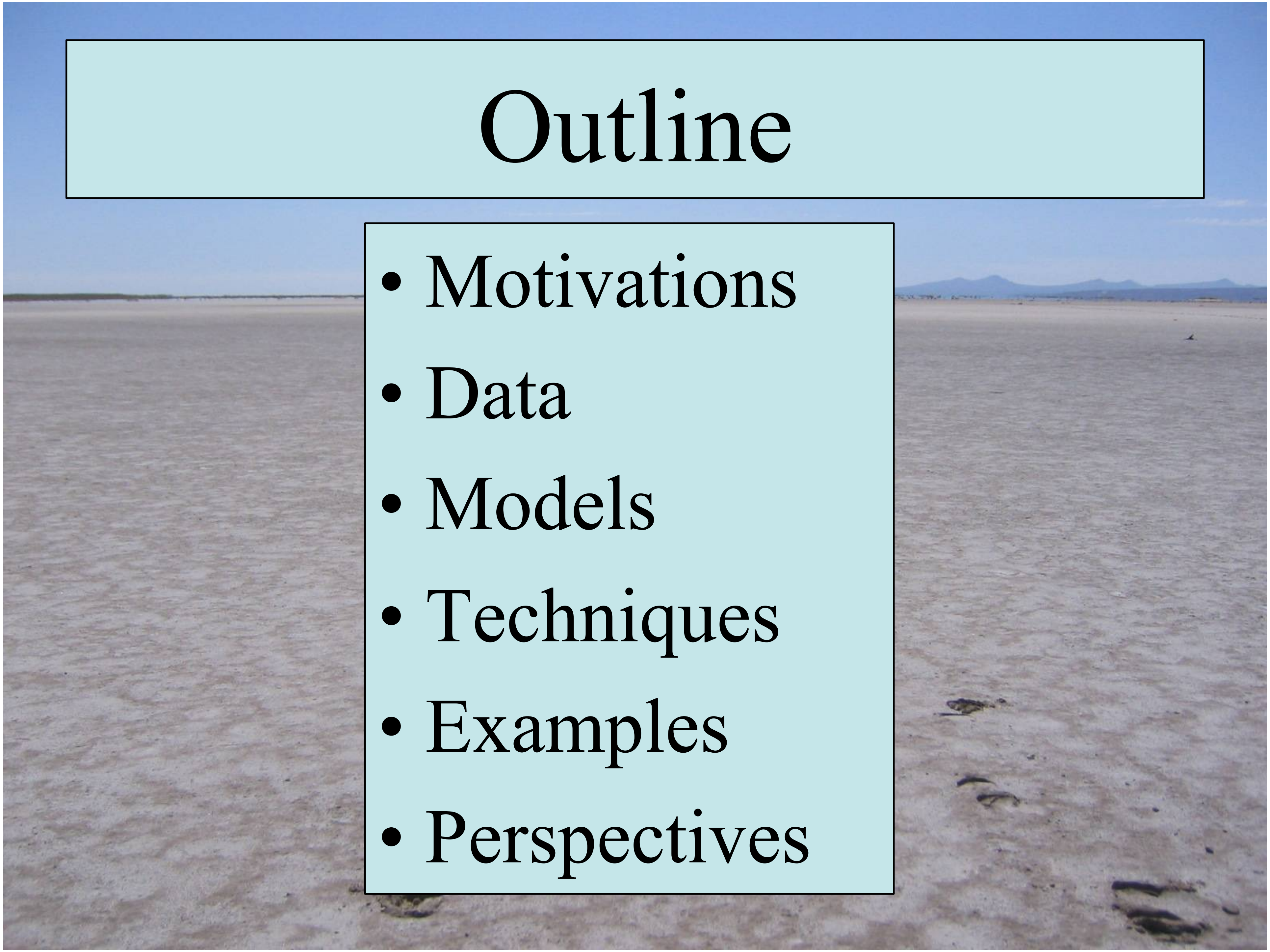
Progress in LHC Luminosity

Instantaneous luminosity



Integrated luminosity





Outline

- Motivations
- Data
- Models
- Techniques
- Examples
- Perspectives

Supersymmetry?

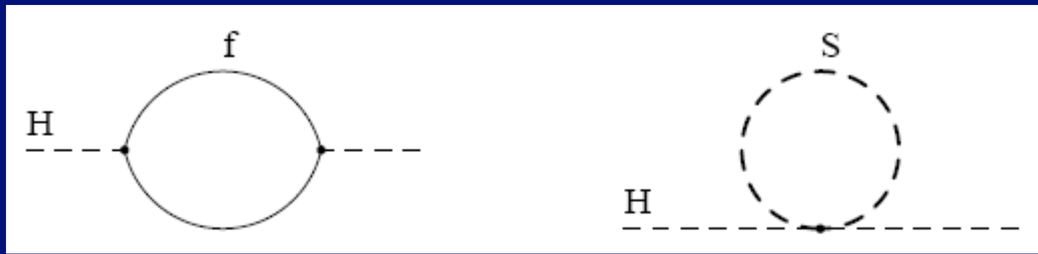
- Would unify matter particles and force particles
- Related particles spinning at different rates

  0 - ½ - 1 - 3/2 - 2

  Higgs - Electron - Photon - Gravitino – Graviton
- Many phenomenological motivations
  - Would help fix particle masses
  - Would help unify forces
  - Predicts light Higgs boson
  - Could fix discrepancy in g_μ - 2
- **Could provide dark matter for the astrophysicists and cosmologists**

Loop Corrections to Higgs Mass^2

- Consider generic fermion and boson loops:



- Each is quadratically divergent: $\int^{\Lambda} d^4k/k^2$

$$\Delta m_H^2 = -\frac{y_f^2}{16\pi^2}[2\Lambda^2 + 6m_f^2 \ln(\Lambda/m_f) + ...]$$

$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}[\Lambda^2 - 2m_S^2 \ln(\Lambda/m_S) + ...]$$

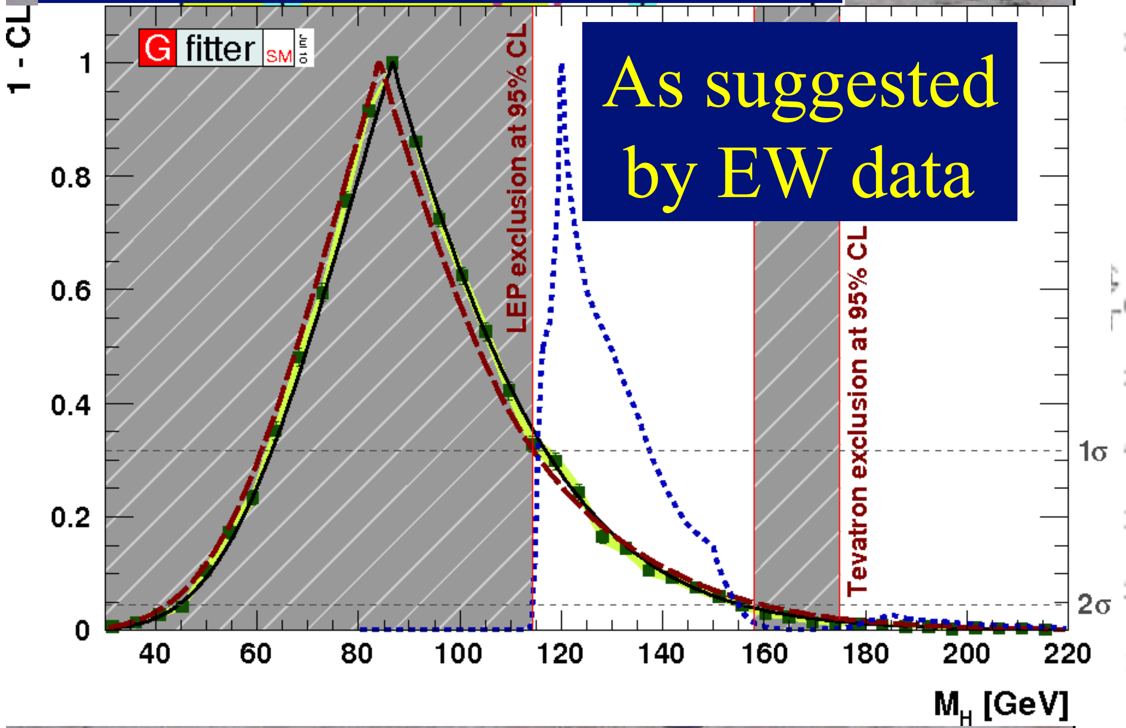
- Leading divergence cancelled if

$\lambda_S = y_f^2$ x 2 **persymmetry!**

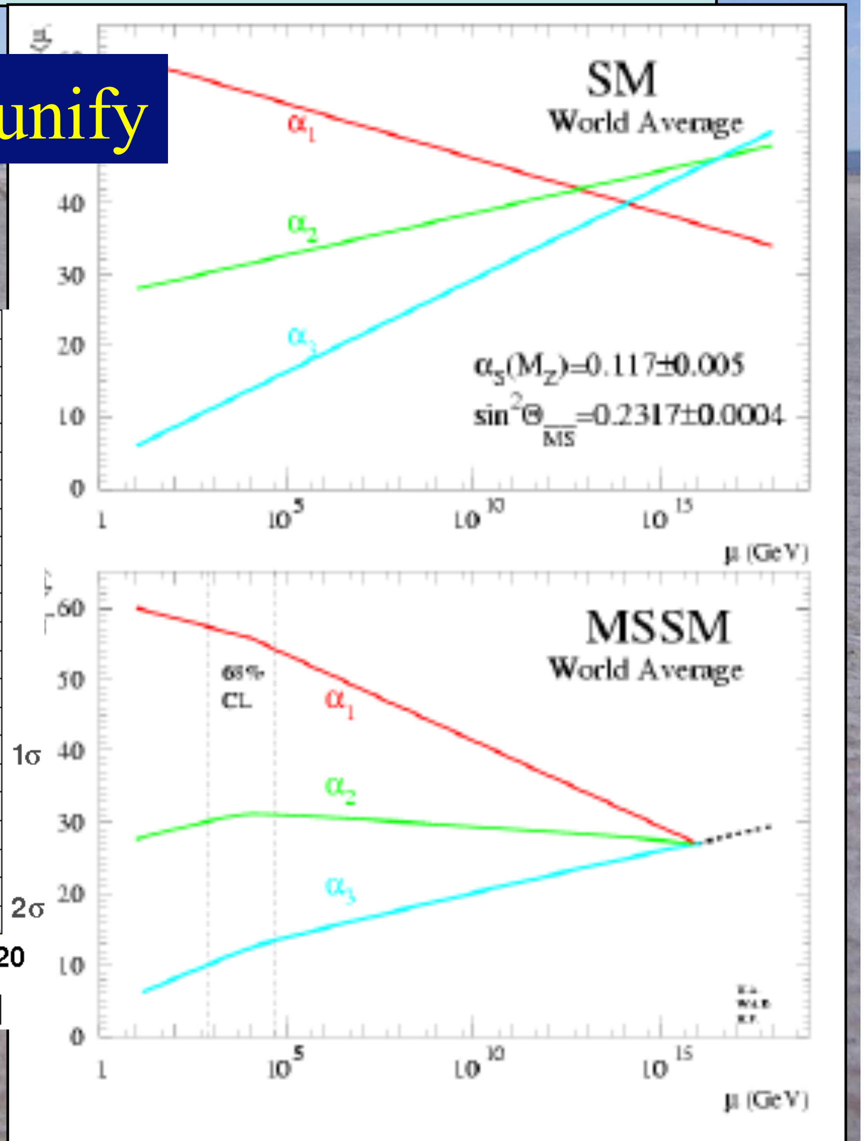
Other Reasons to like Susy

It enables the gauge couplings to unify

It predicts $m_H < 150$ GeV



As suggested by EW data



Minimal Supersymmetric Extension of Standard Model (MSSM)

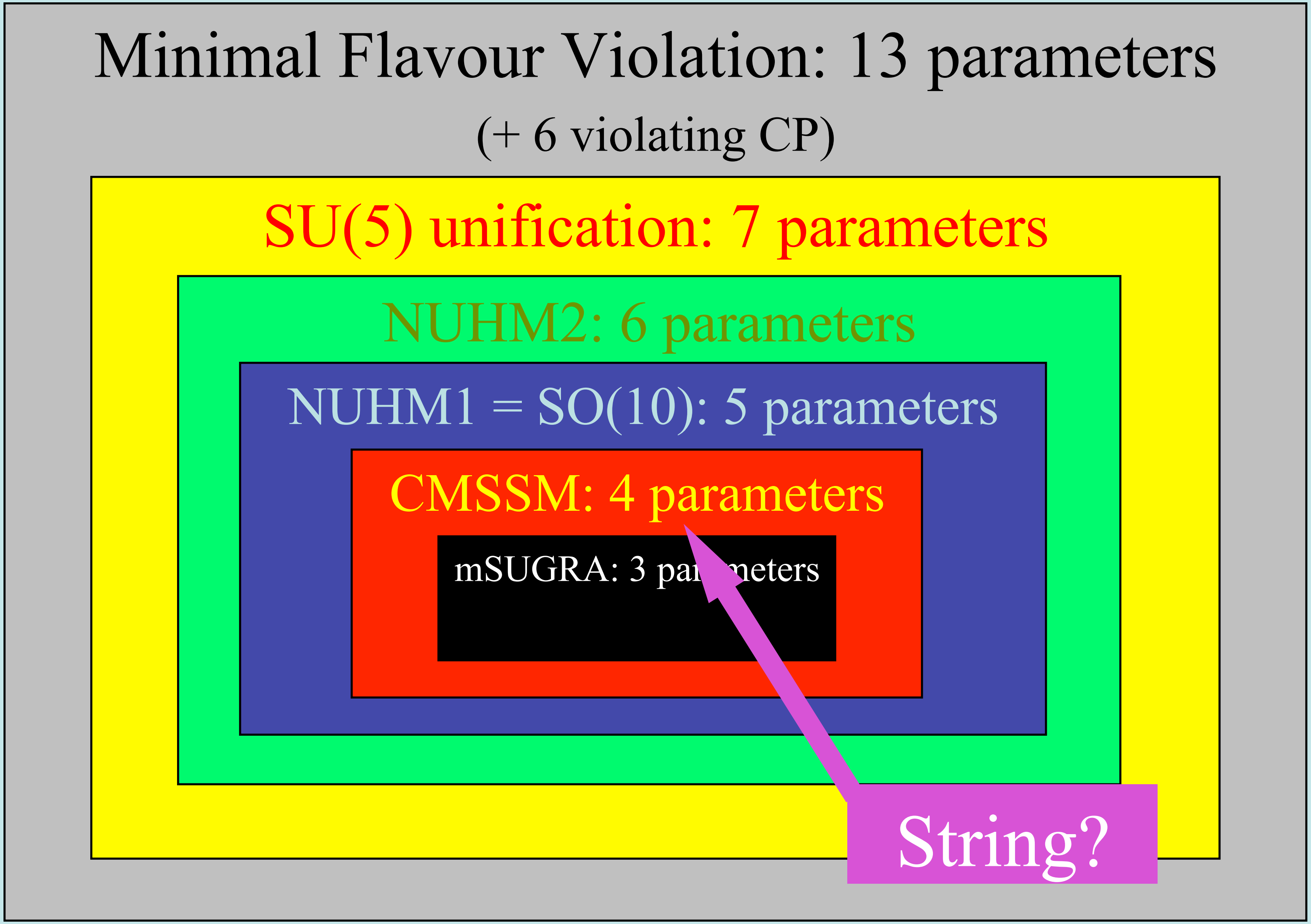
- Double up the known particles:

$$\begin{pmatrix} \frac{1}{2} \\ 0 \end{pmatrix} \; e.g., \; \begin{pmatrix} \ell \,(lepton) \\ \tilde{\ell} \,(slepton) \end{pmatrix} or \begin{pmatrix} q \,(quark) \\ \tilde{q} \,(squark) \end{pmatrix}$$

$$\begin{pmatrix} 1 \\ \frac{1}{2} \end{pmatrix} \; e.g., \; \begin{pmatrix} \gamma \,(photon) \\ \tilde{\gamma} \,(photino) \end{pmatrix} or \begin{pmatrix} g \,(gluon) \\ \tilde{g} \,(gluino) \end{pmatrix}$$

- Two Higgs doublets
  - 5 physical Higgs bosons:
  - 3 neutral, 2 charged
- Lightest neutral supersymmetric Higgs looks like the single Higgs in the Standard Model

MSSM: > 100 parameters



Supersymmetric Models to Study

- Gravity-mediated:
  - NUHM2
    - as below, m ≠ m
  - NUHM1
    - as below, c
  - CMSSM
    - m_0, $m_{1/2}$, ta
  - VCMSSM
    - as above, & A_0
  - mSUGRA
    - as above, & m
  - RPV CMSSM

Also studied in global fits

Most studied in global fits

Some Global fits

- Other SUSY ✕ models:
  - Gauge-mediated
  - Anomaly-mediated
  - Mixed modulus-anomaly-mediated
  - Phenomenological 19-parameter MSSM

Less studied in global fits

If model has N parameters, sample 100 values/parameter: 10^{2N} points, e.g., 10^8 in CMSSM

Data

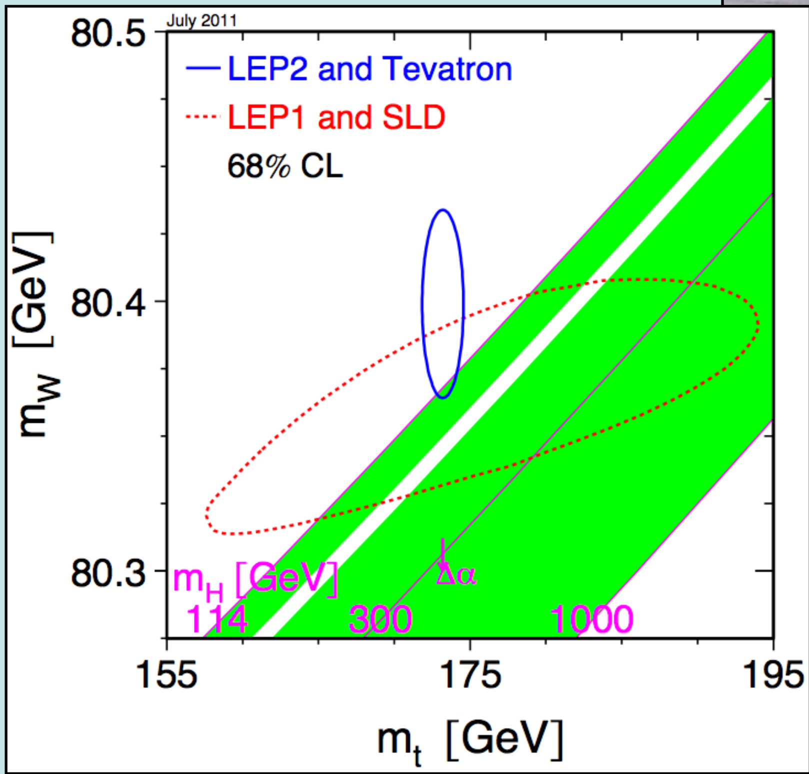
- **Electroweak precision observables**
- **Flavour physics observables**
- g_μ - 2
- Higgs mass
- Dark matter
- **LHC**

MasterCode: O.Buchmueller, JE et al.

Observable	Source Th./Ex.	Constraint
m_t [GeV]	[39]	173.2 ± 0.90
$\Delta\alpha^{(5)}_{\rm had}(m_Z)$	[38]	0.02749 ± 0.00010
M_Z [GeV]	[40]	91.1875 ± 0.0021
Γ_Z [GeV]	[24] / [40]	$2.4952 \pm 0.0023 \pm 0.001_{\rm SUSY}$
$\sigma^0_{\rm had}$ [nb]	[24] / [40]	41.540 ± 0.037
R_l	[24] / [40]	20.767 ± 0.025
$A_{\rm fb}(\ell)$	[24] / [40]	0.01714 ± 0.00095
$A_\ell(P_\tau)$	[24] / [40]	0.1465 ± 0.0032
$R_{\rm b}$	[24] / [40]	0.21629 ± 0.00066
$R_{\rm c}$	[24] / [40]	0.1721 ± 0.0030
$A_{\rm fb}(b)$	[24] / [40]	0.0992 ± 0.0016
$A_{\rm fb}(c)$	[24] / [40]	0.0707 ± 0.0035
A_b	[24] / [40]	0.923 ± 0.020
A_c	[24] / [40]	0.670 ± 0.027
A_ℓ(SLD)	[24] / [40]	0.1513 ± 0.0021
$\sin^2\theta^\ell_{\rm w}(Q_{\rm fb})$	[24] / [40]	0.2324 ± 0.0012
M_W [GeV]	[24] / [40]	$80.399 \pm 0.023 \pm 0.010_{\rm SUSY}$
${\rm BR}^{\rm EXP}_{b\to s\gamma}/{\rm BR}^{\rm SM}_{b\to s\gamma}$	[41] / [42]	$1.117 \pm 0.076_{\rm EXP}$ $\pm 0.082_{\rm SM} \pm 0.050_{\rm SUSY}$
${\rm BR}(B_s \to \mu^+\mu^-)$	[27] / [37]	$(< 1.08 \pm 0.02_{\rm SUSY}) \times 10^{-8}$
${\rm BR}^{\rm EXP}_{B\to\tau\nu}/{\rm BR}^{\rm SM}_{B\to\tau\nu}$	[27] / [42]	$1.43 \pm 0.43_{\rm EXP+TH}$
${\rm BR}(B_d \to \mu^+\mu^-)$	[27] / [42]	$< (4.6 \pm 0.01_{\rm SUSY}) \times 10^{-9}$
${\rm BR}^{\rm EXP}_{B\to X_s\ell\ell}/{\rm BR}^{\rm SM}_{B\to X_s\ell\ell}$	[43]/ [42]	0.99 ± 0.32
${\rm BR}^{\rm EXP}_{K\to\mu\nu}/{\rm BR}^{\rm SM}_{K\to\mu\nu}$	[27] / [44]	$1.008 \pm 0.014_{\rm EXP+TH}$
${\rm BR}^{\rm EXP}_{K\to\pi\nu\bar\nu}/{\rm BR}^{\rm SM}_{K\to\pi\nu\bar\nu}$	[45]/ [46]	< 4.5
$\Delta M^{\rm EXP}_{B_s}/\Delta M^{\rm SM}_{B_s}$	[45] / [47, 48]	$0.97 \pm 0.01_{\rm EXP} \pm 0.27_{\rm SM}$
$\frac{(\Delta M^{\rm EXP}_{B_s}/\Delta M^{\rm SM}_{B_s})}{(\Delta M^{\rm EXP}_{B_d}/\Delta M^{\rm SM}_{B_d})}$	[27] / [42, 47, 48]	$1.00 \pm 0.01_{\rm EXP} \pm 0.13_{\rm SM}$
$\Delta\epsilon^{\rm EXP}_K/\Delta\epsilon^{\rm SM}_K$	[45] / [47, 48]	$1.08 \pm 0.14_{\rm EXP+TH}$
$a^{\rm EXP}_\mu - a^{\rm SM}_\mu$	[49] / [38, 50]	$(30.2 \pm 8.8 \pm 2.0_{\rm SUSY}) \times 10^{-10}$
M_h [GeV]	[26] / [51, 52]	$> 114.4 \pm 1.5_{\rm SUSY}$
$\Omega_{\rm CDM}h^2$	[29] / [53]	$0.1109 \pm 0.0056 \pm 0.012_{\rm SUSY}$
$\sigma^{\rm SI}_p$	[23]	$(m_{\tilde\chi^0_1}, \sigma^{\rm SI}_p)$ plane
jets $+ \not{E}_T$	[16, 18]	$(m_0, m_{1/2})$ plane
$H/A, H^\pm$	[19]	$(M_A, \tan\beta)$ plane

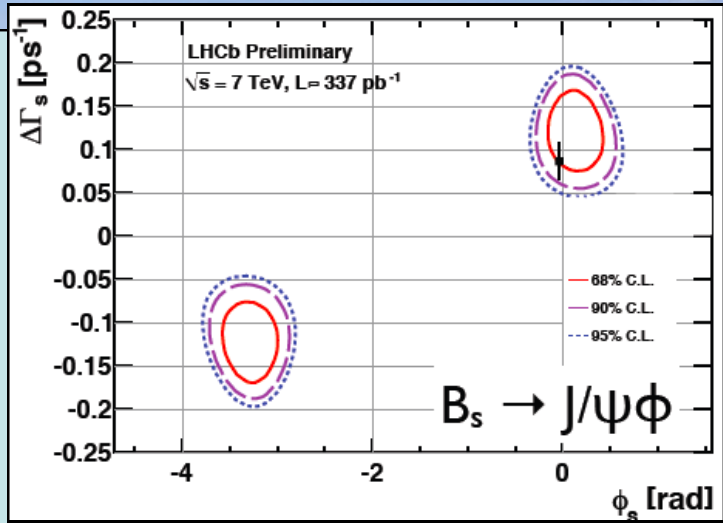
Electroweak Precision Observables

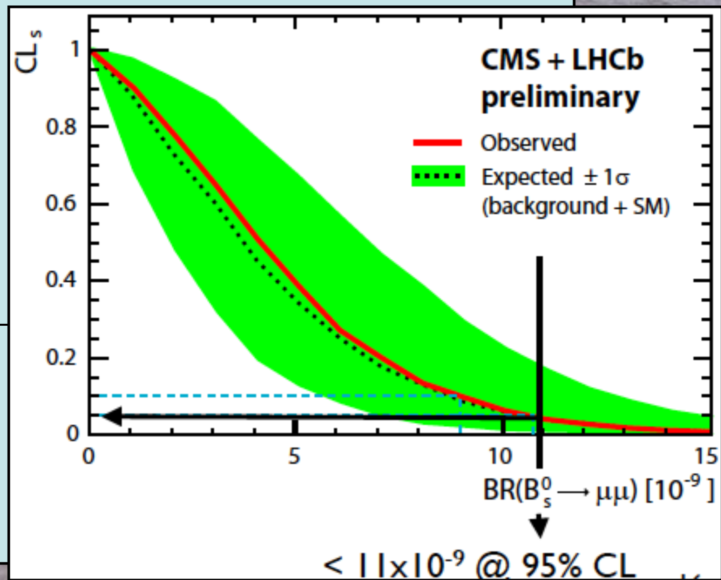
- Inclusion essential for fair comparison with Standard Model
- Some observables may be significantly different
  - E.g., m_W, $A_{fb}(b)$
  - Advantage for SUSY?
- Some may not be changed significantly
  - Should be counted against/for all models



Flavour Physics Observables

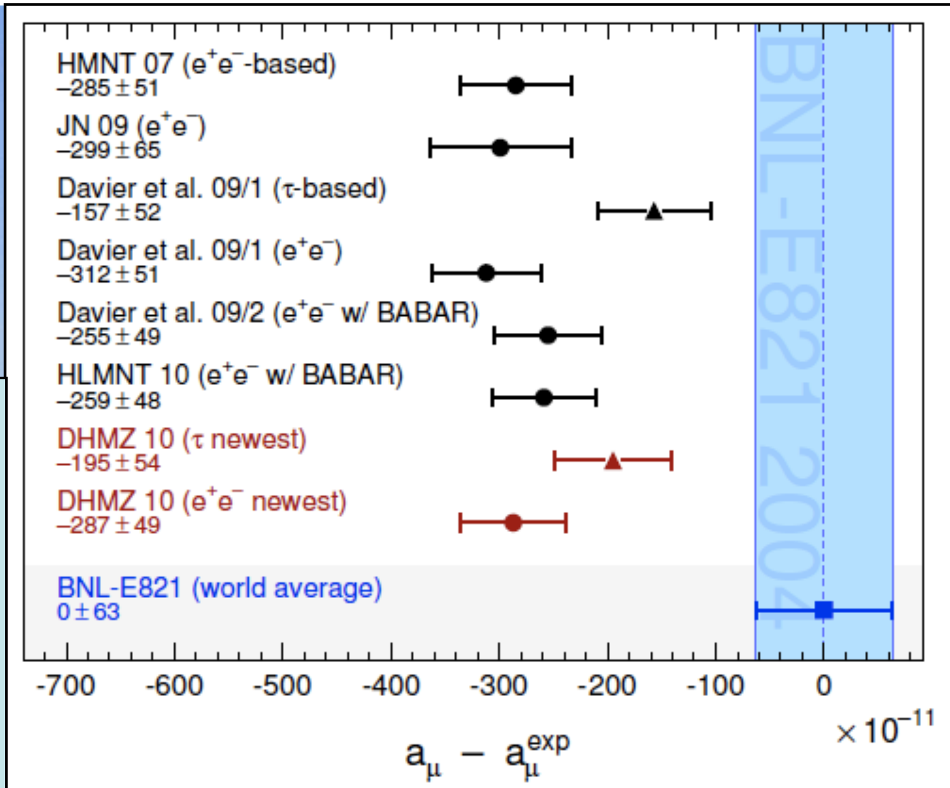
- Inclusion requires additional hypotheses
  - E.g., minimal flavour violation
- Many anomalies reported
  - E.g., top production asymmetry, dimuon asymmetry, $B_s \rightarrow J/\psi\ \varphi$
    - Difficult to interpret within SUSY
    - Significant progress with $B_s \rightarrow \mu$
    - Valuable constraint on SUSY models

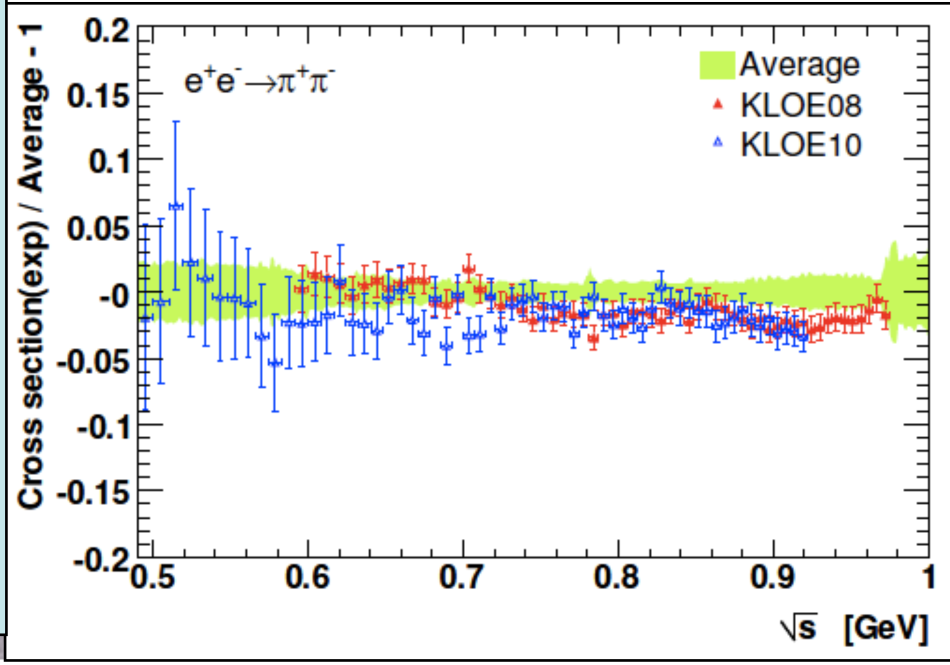




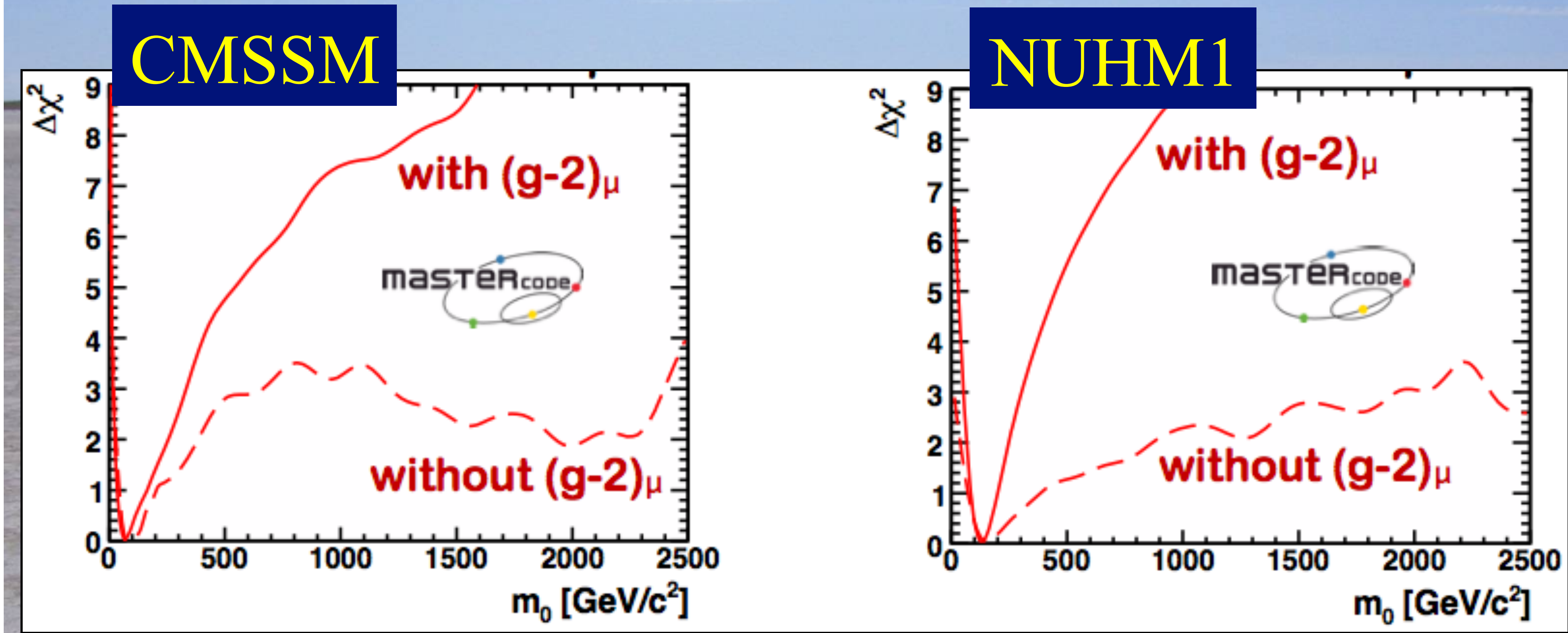
Quo Vadis g_μ - 2?

- Strong discrepancy between BNL experiment and e^+e^- data:
  - now ~ 3.6 σ
- Better agreement between e^+e^- experiments
- Increased discrepancy between BNL experiment and τ decay data
  - now ~ 2.4 σ
- Convergence between e^+e^- experiments and τ decay data
- **More credibility?**





To $g_\mu - 2$ or not to $g_\mu - 2$?



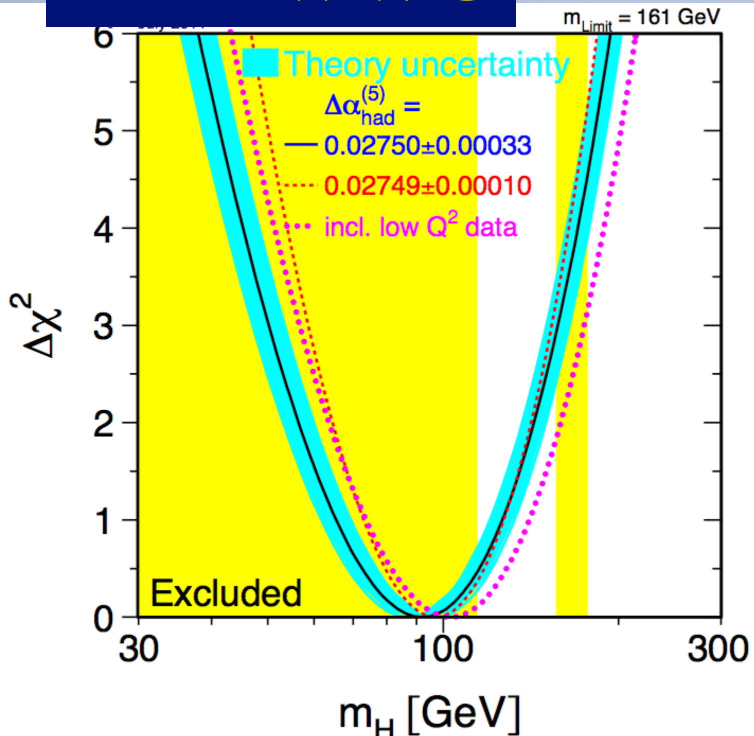
Pre-LHC fits:

Mild preference for small masses even without $g_\mu - 2$?

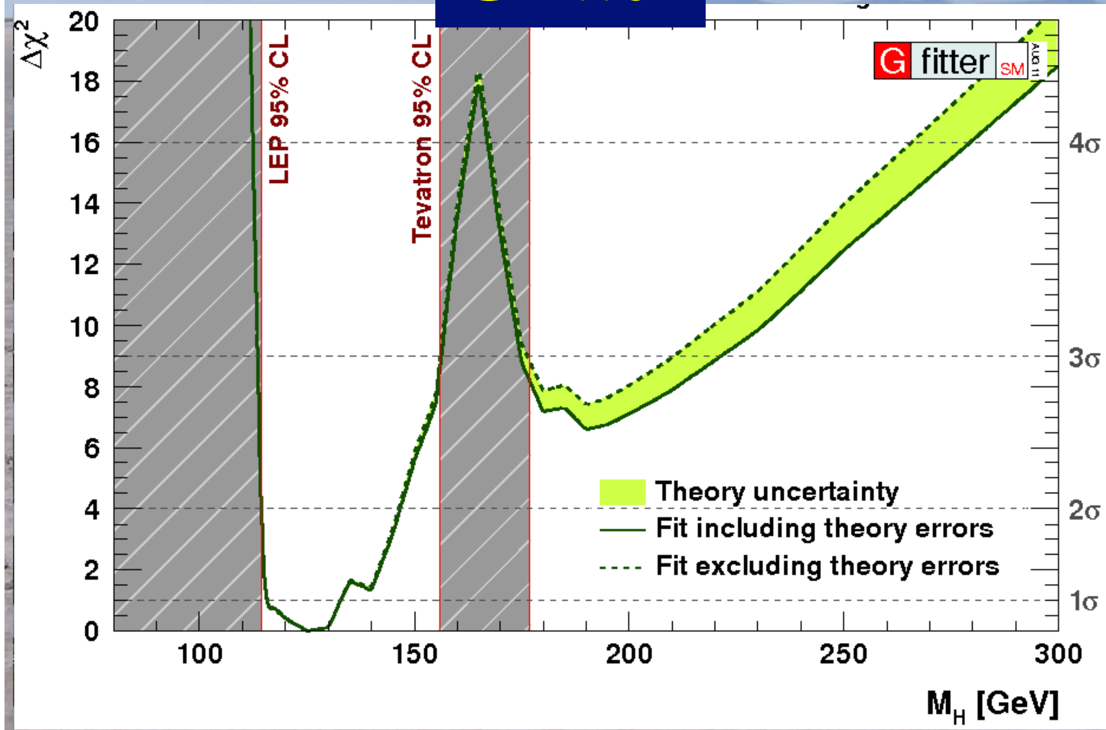
MasterCode: O.Buchmueller, JE et al.

m_H: Blue Band vs Green Band

LEPEWWG



Gfitter



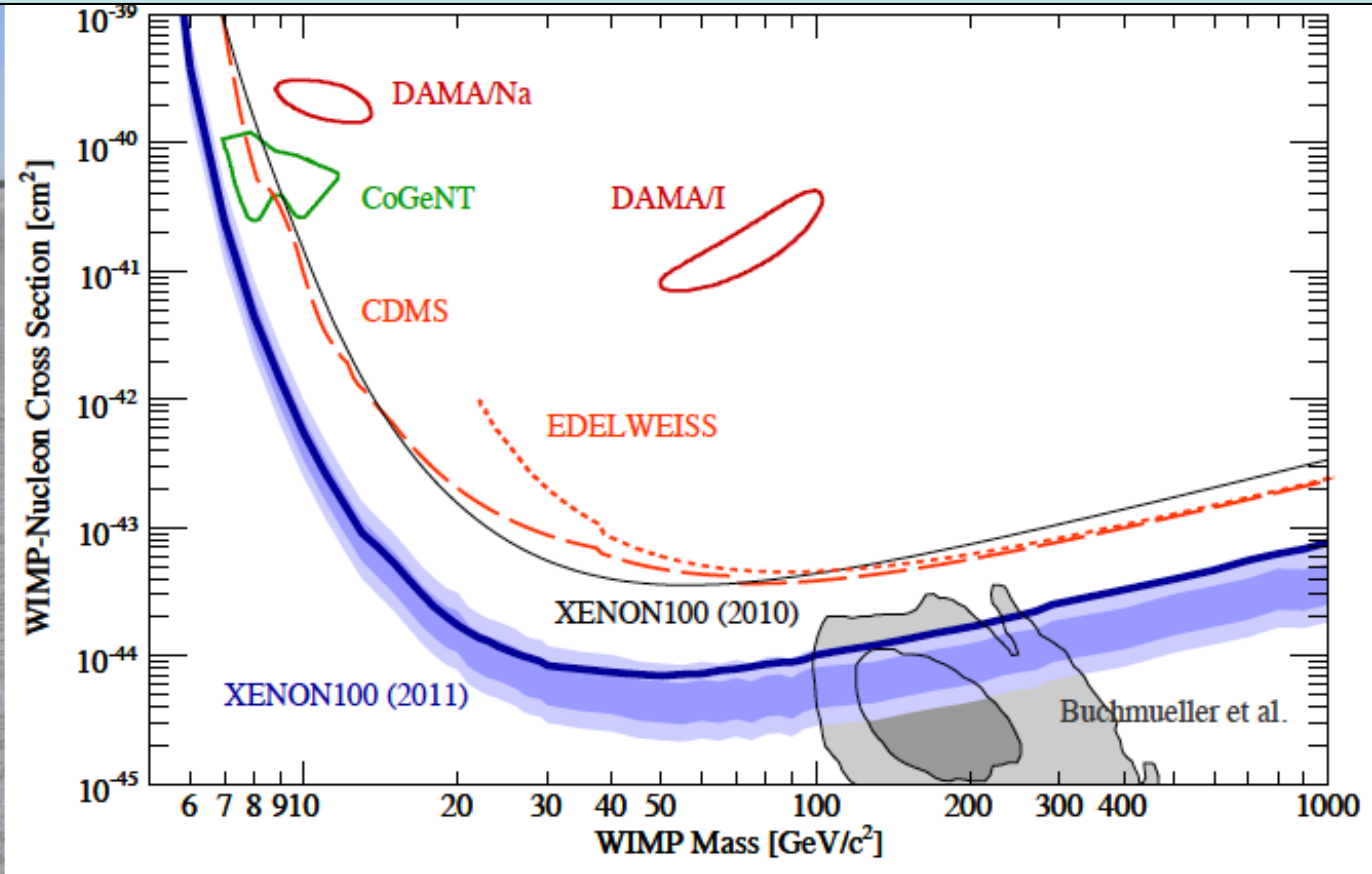
Precision data vs LEP, Tevatron

Combination with LHC

Dark Matter Observables

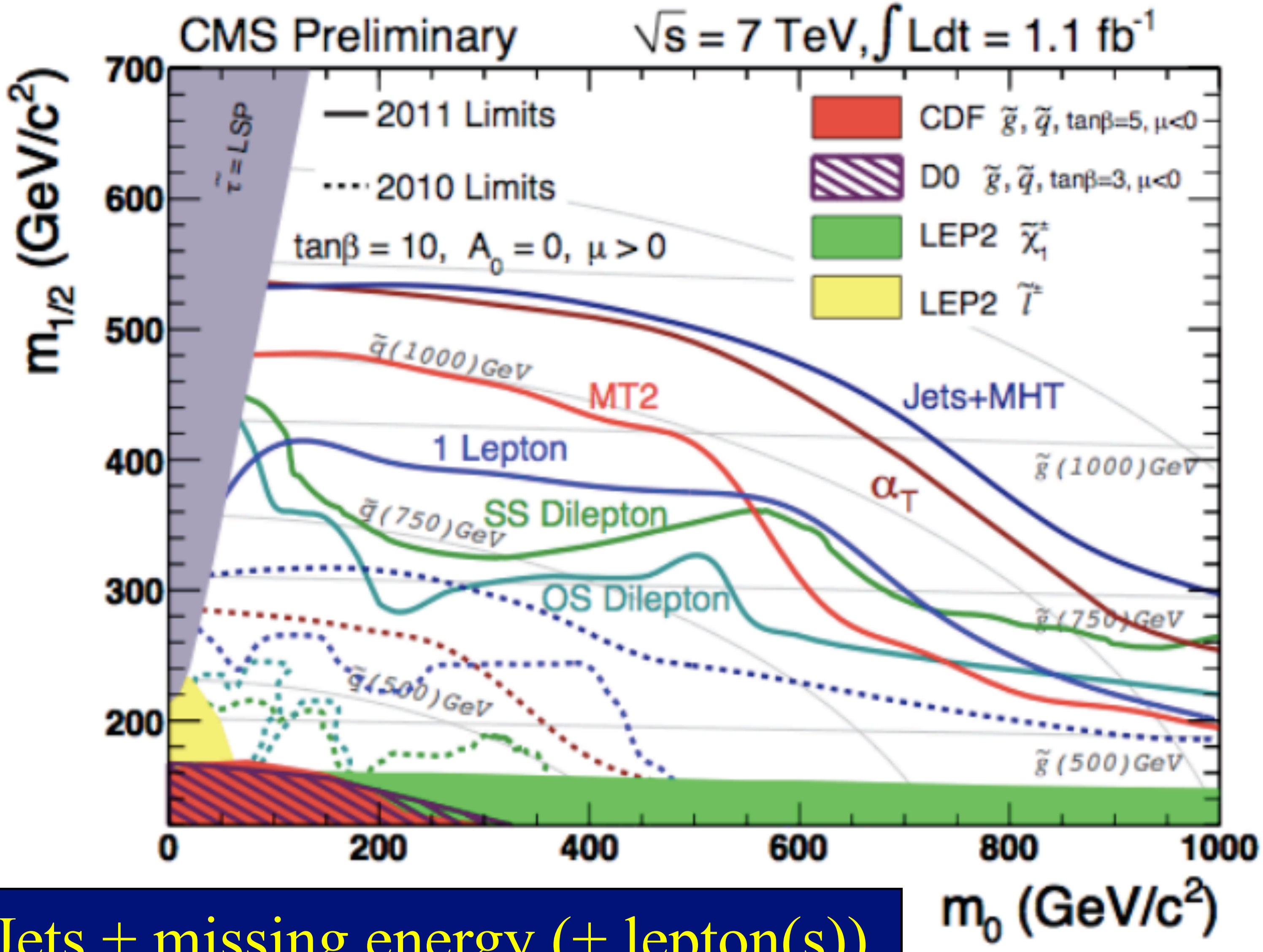
- Cosmological cold dark matter density
  - $\Omega_{CDM} h^2 = 0.1109 \pm 0.0056$
- Reduces dimensionality of SUSY space by ~ 1
  - Could be other sources of DM: little effect
- Upper limit on spin-independent scattering
- Other astrophysical constraints?
  - Annihilations inside Sun/Earth ➔neutrinos?
  - Anomalies in cosmic-ray γ/e+/e- spectra?
- Not explicable in models discussed here

XENON100 Experiment



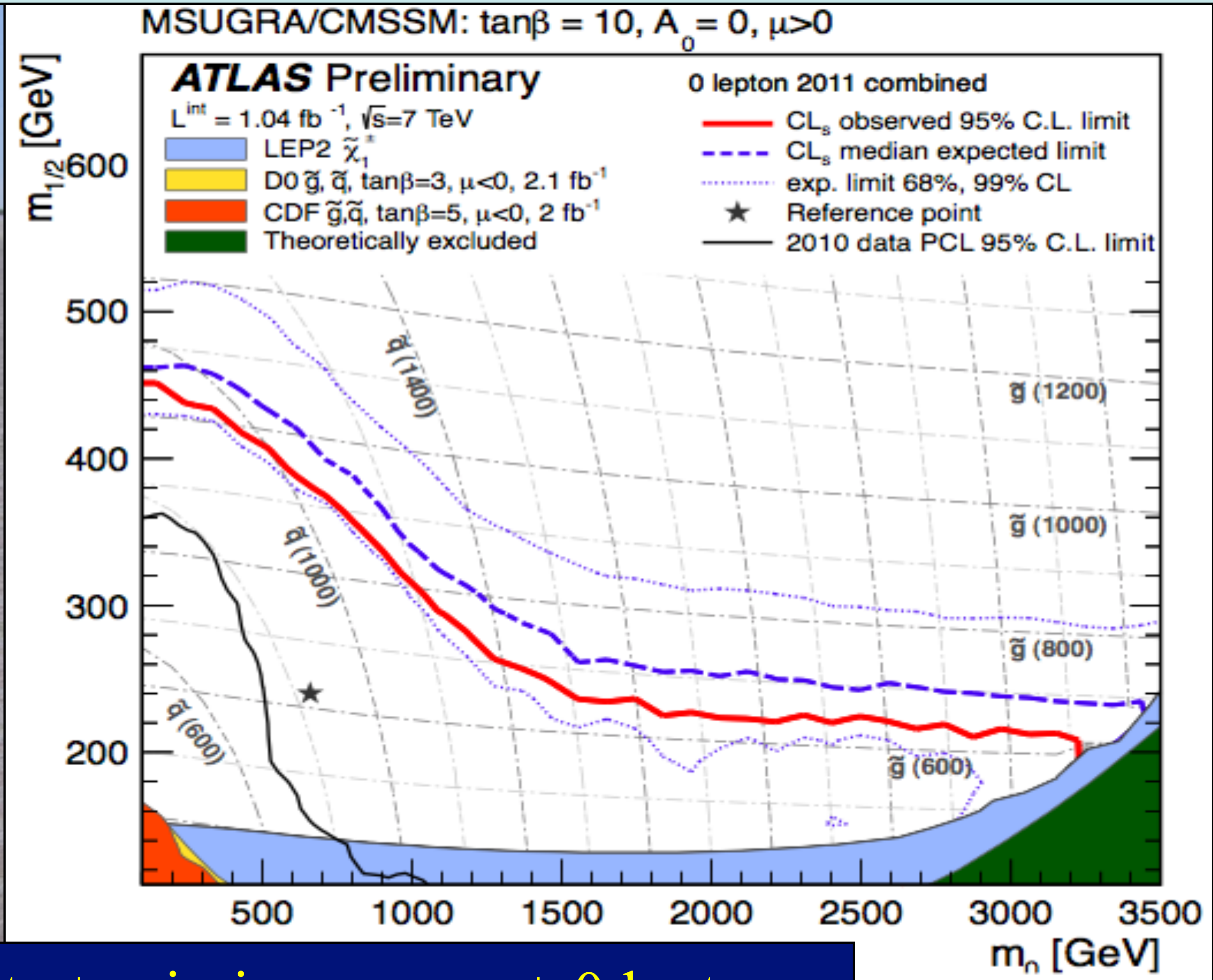
Aprile et al: arXiv:1104.2549

Supersymmetry Searches in CMS



Jets + missing energy (+ lepton(s))

Supersymmetry Searches in ATLAS



Jets + missing energy + 0 lepton

Impact of LHC on the CMSSM

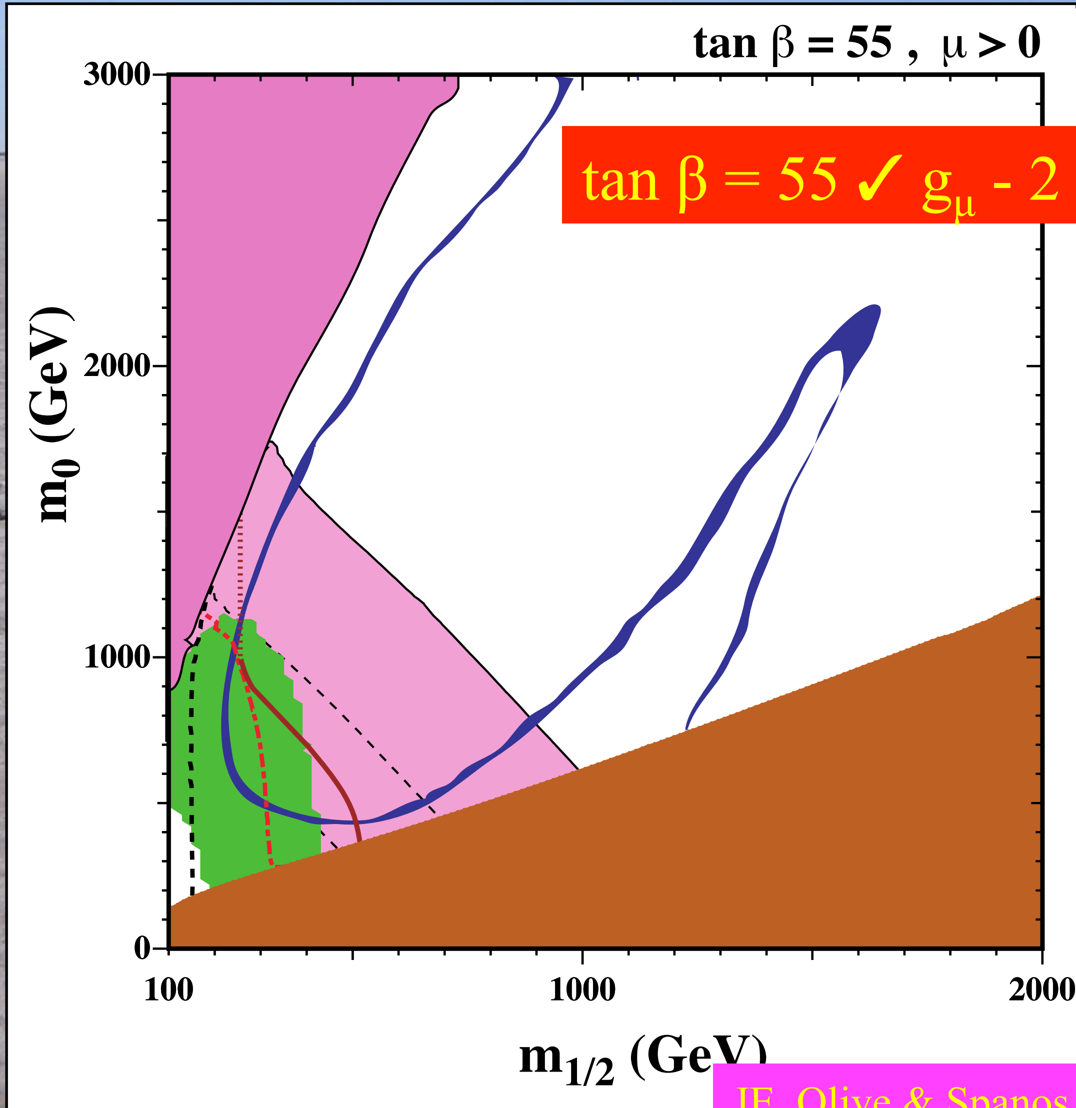
Assuming the lightest sparticle is a neutralino

Excluded because stau LSP

Excluded by b → s gamma

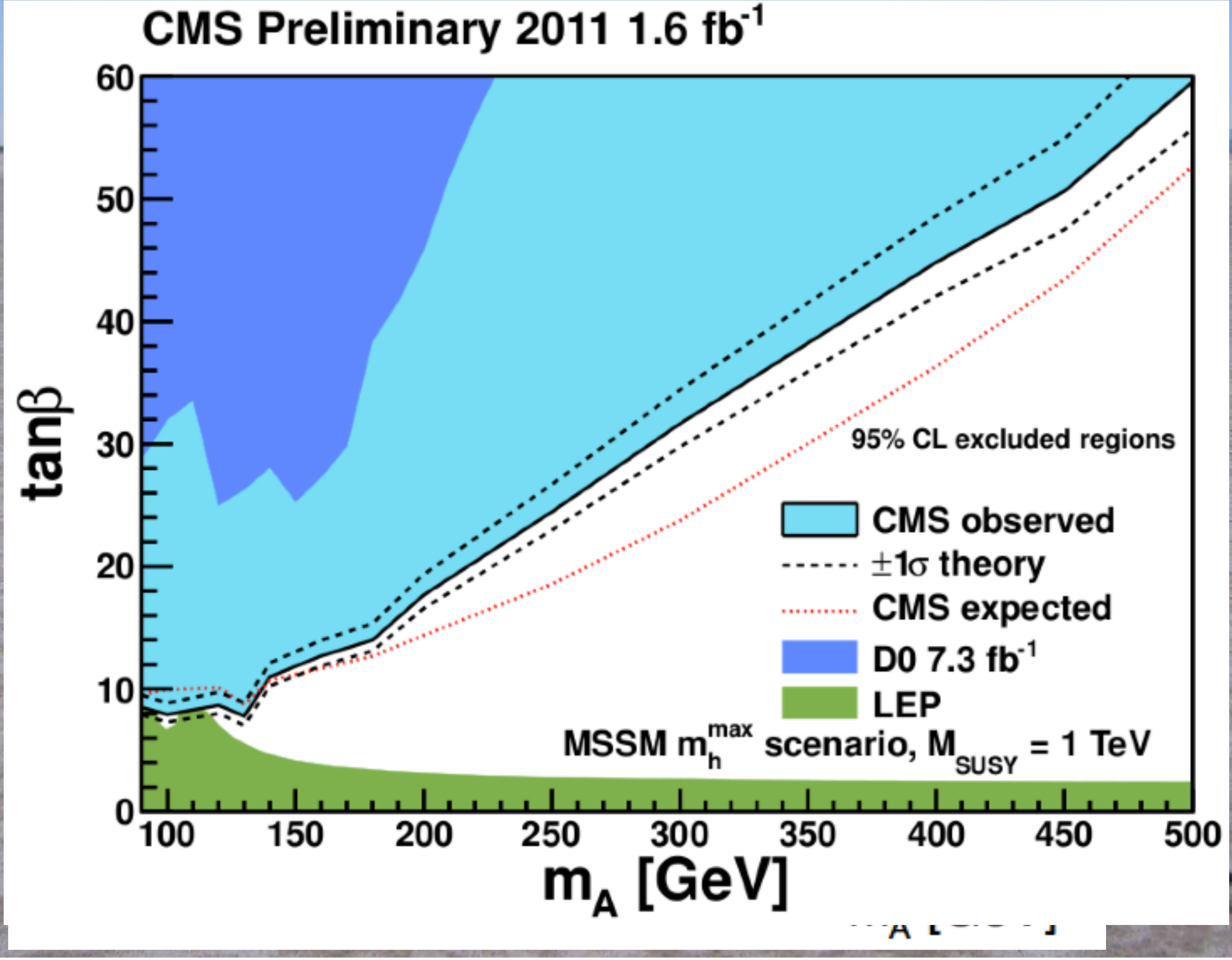
WMAP constraint on CDM density

Preferred (?) by latest g - 2



JE, Olive & Spanos

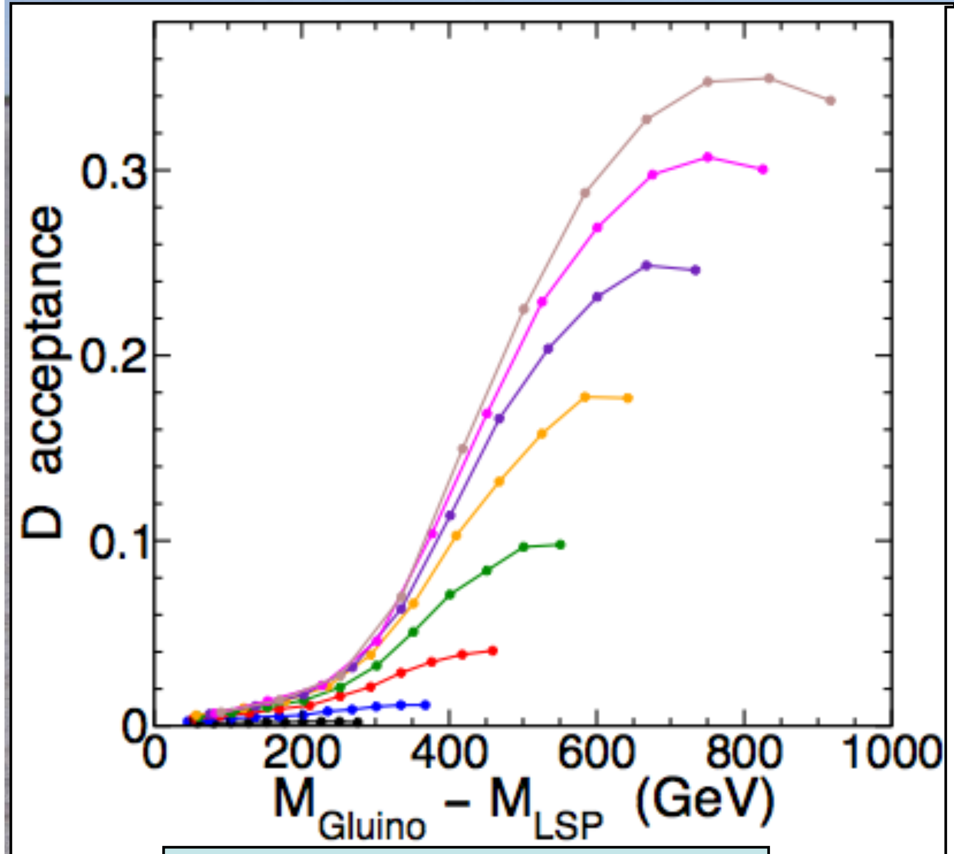
Limits on Heavy MSSM Higgses



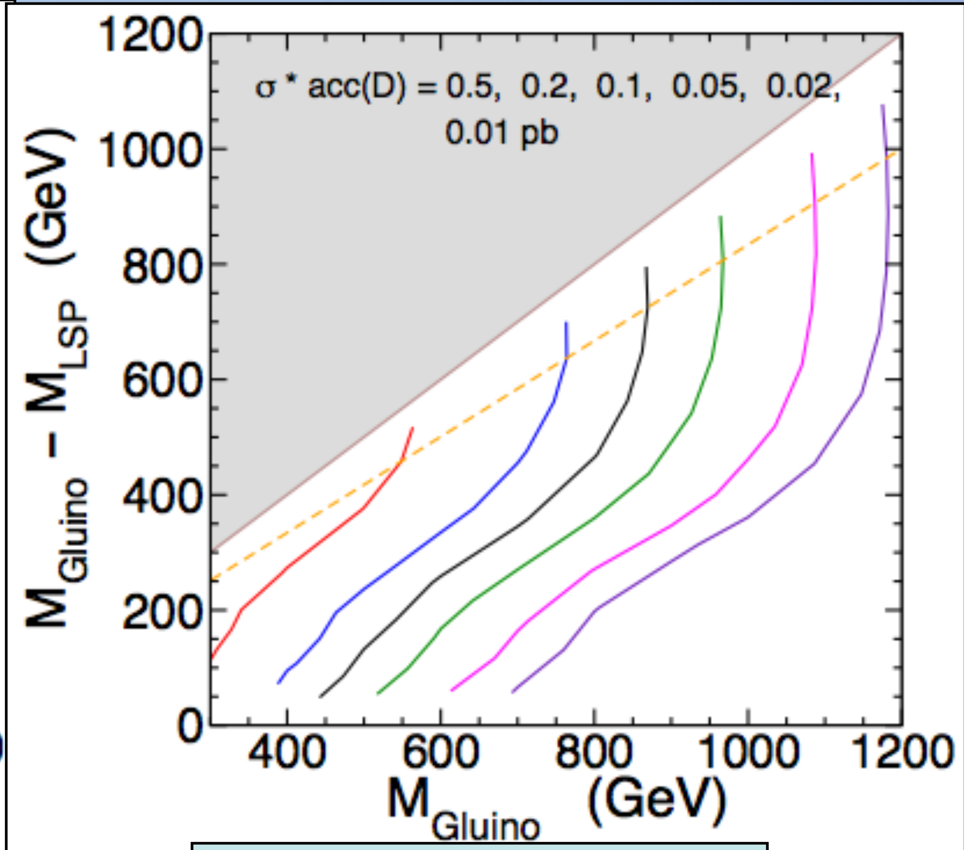
Meta-Analyses: Cuts vs Likelihood

- Theorists seek to combine many constraints
- **Simply imposing 95% CL contours as cuts is inadequate**
  - Seek to construct global likelihood function
- **Want more information from experiments: several likelihood contours**
  - Can be used to check our simulations
- Otherwise, we will resort to unreliable estimates/guesses ☹

Current LHC Searches have Reduced Sensitivity to Compressed Spectra



Acceptance of typical ATLAS MET search



Exclusion by typical ATLAS MET search

LeCompte & Martin

Bayesian vs Frequentist

- Bayesian: *"probability is a measure of the degree of belief about a proposition"*

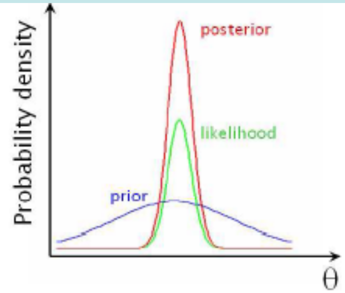
Bayes' theorem: posterior pdf

$$p(\theta, \psi | d) = \frac{p(d|\xi)\pi(\theta,\psi)}{p(d)}$$

$p(d|\xi) = \mathcal{L}$: likelihood

$\pi(\theta, \psi)$: prior pdf

$p(d)$: evidence (normalization factor)



$$\text{posterior} = \frac{\text{likelihood} \times \text{prior}}{\text{normalization factor}}$$

- Frequentist: *"probability is the number of times the event occurs over the total number of trials, in the limit of an infinite series of equiprobable repetitions"*
- Louis Lyons: *"Bayesians address the question everyone is interested in by using assumptions no–one believes, while frequentists use impeccable logic to deal with an issue of no interest to anyone"*

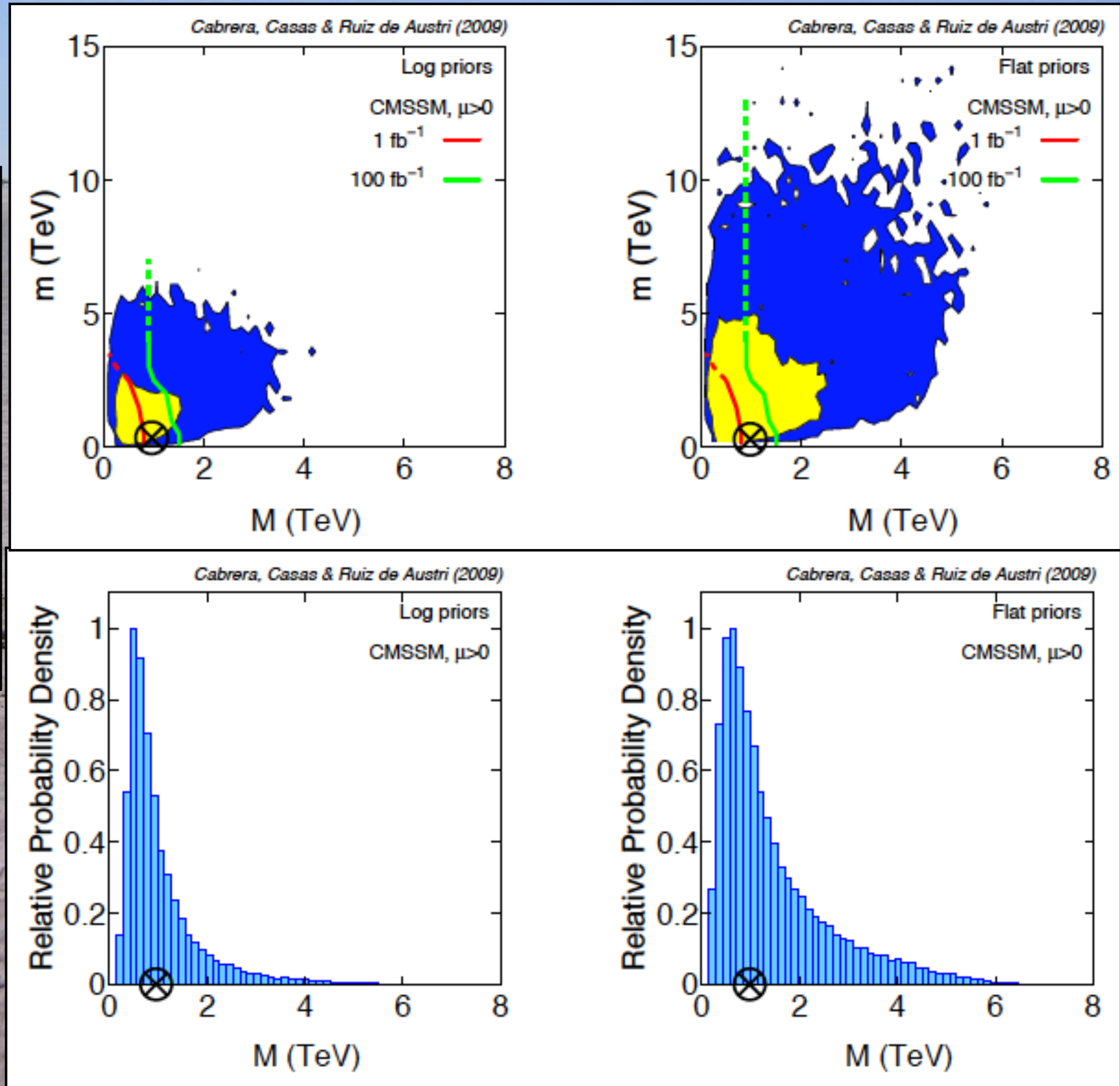
Roszkowski

Sensitivities to Bayesian Priors

Pre-LHC:
Logarithmic vs flat

- $(m_{1/2}, m_0)$ plane

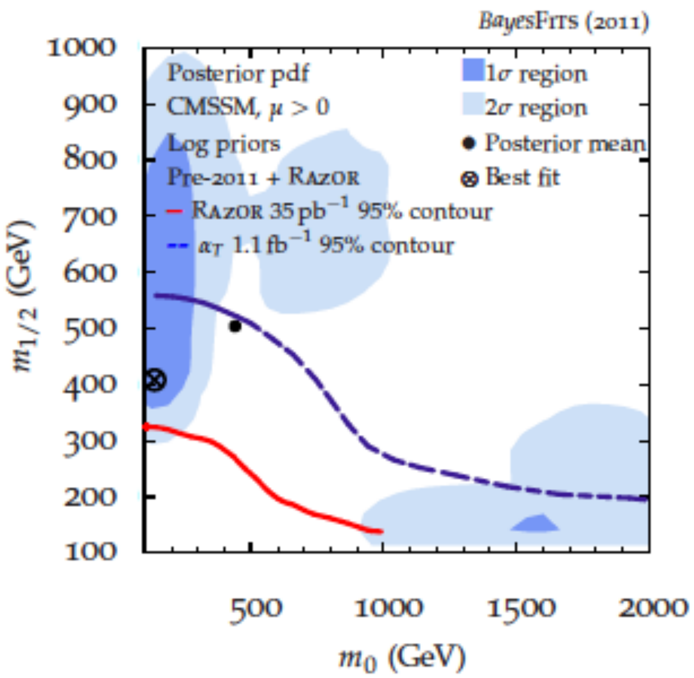
- Probability density for $m_{1/2}$



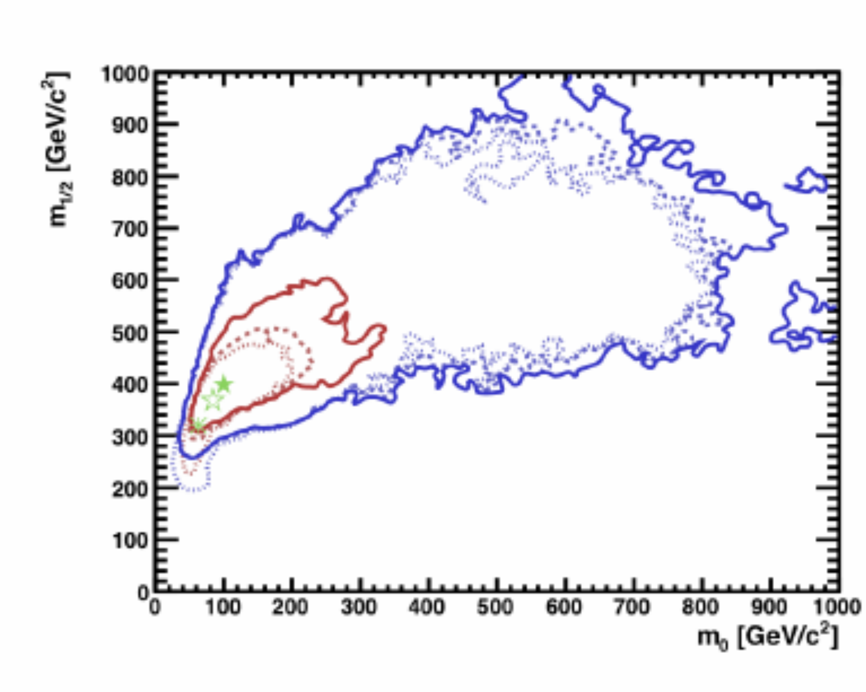
Cabrera, Casas & Ruiz de Austri

To Focus-Point or not to Focus-Point?

Bayesian pdf



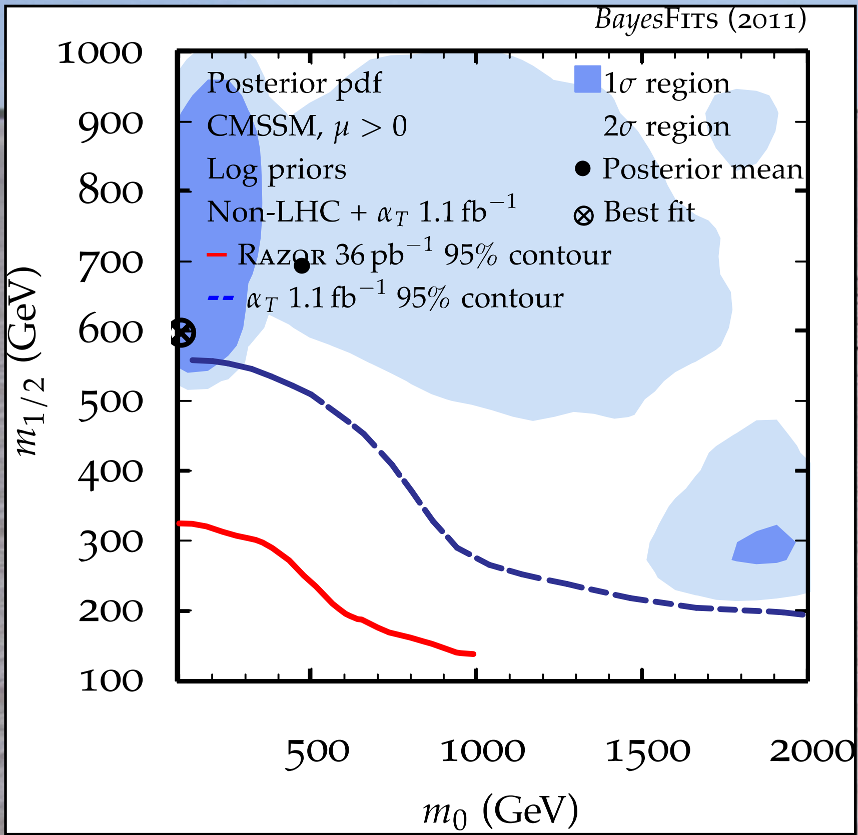
MasterCode



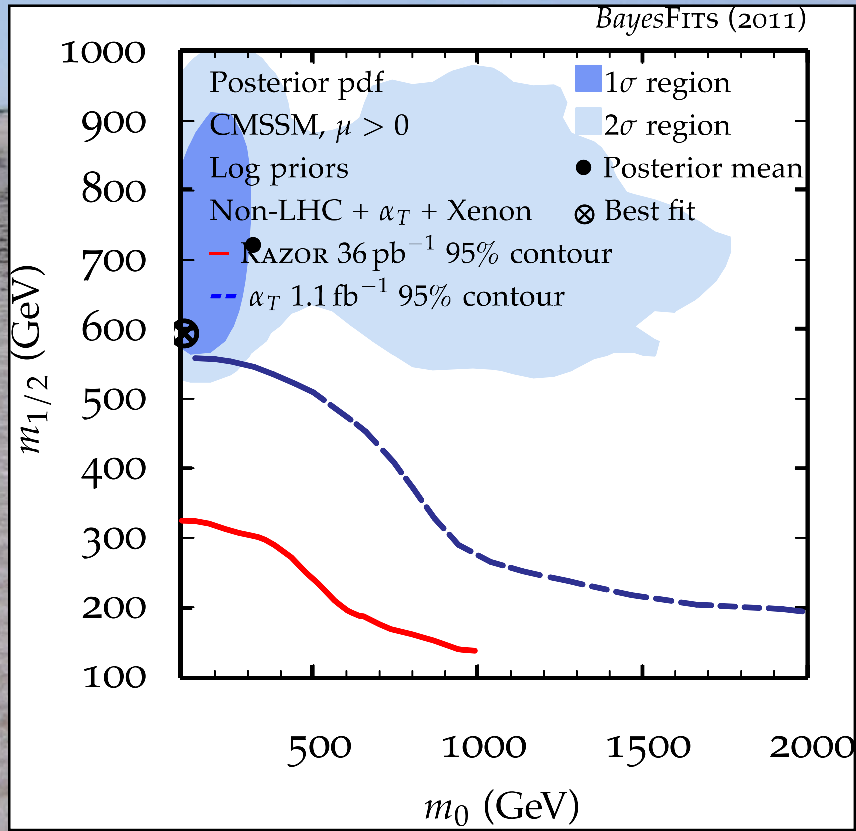
- reasonable agreement in the $m_{1/2} \gtrsim m_0$ region
- disagreement about large m_0 region

BayesFITS: Fowlie, Kalinowski,, Kazana, Roszkowski, Tsai ...

To Focus-Point or not to Focus-Point?



1/fb LHC data, no XENON100
Focus-point remains

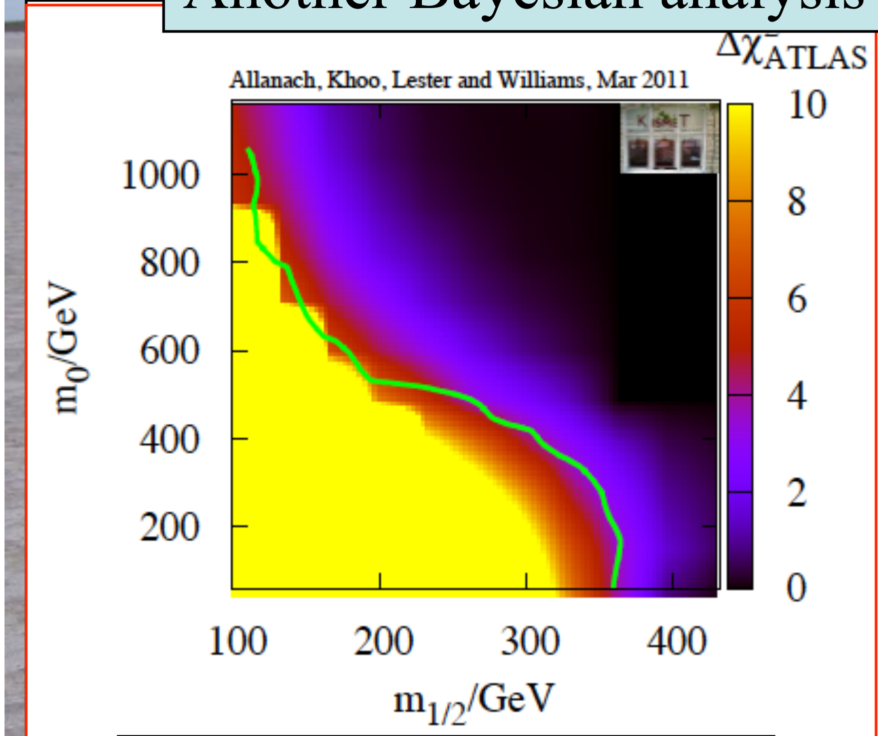


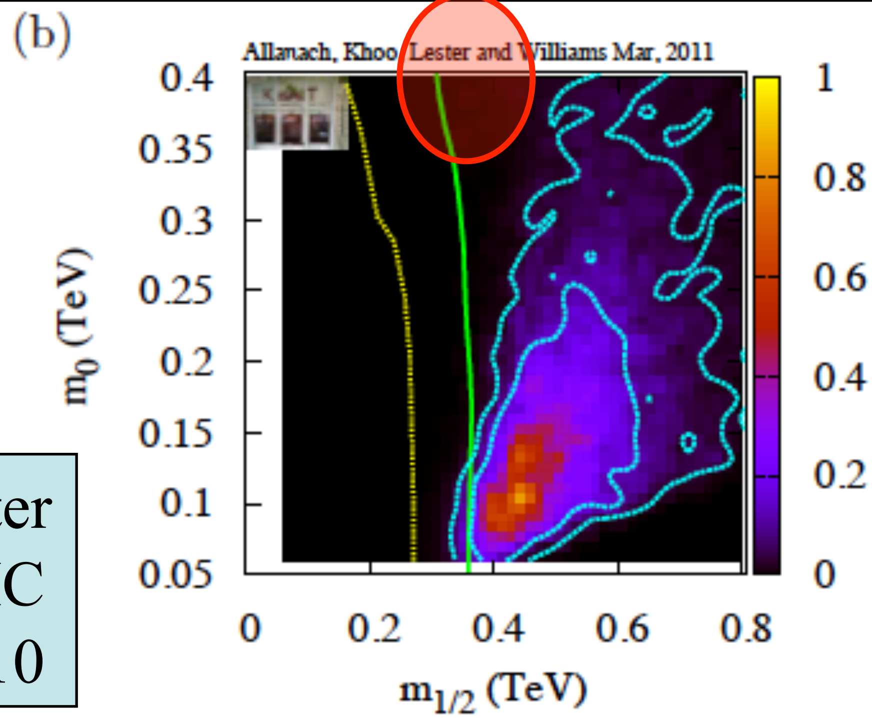
1/fb LHC data, with XENON100
Focus-point disappears

BayesFITS: Fowlie, Kalinowski,, Kazana, Roszkowski, Tsai ...

To Focus-Point or not to Focus-Point?

Another Bayesian analysis …





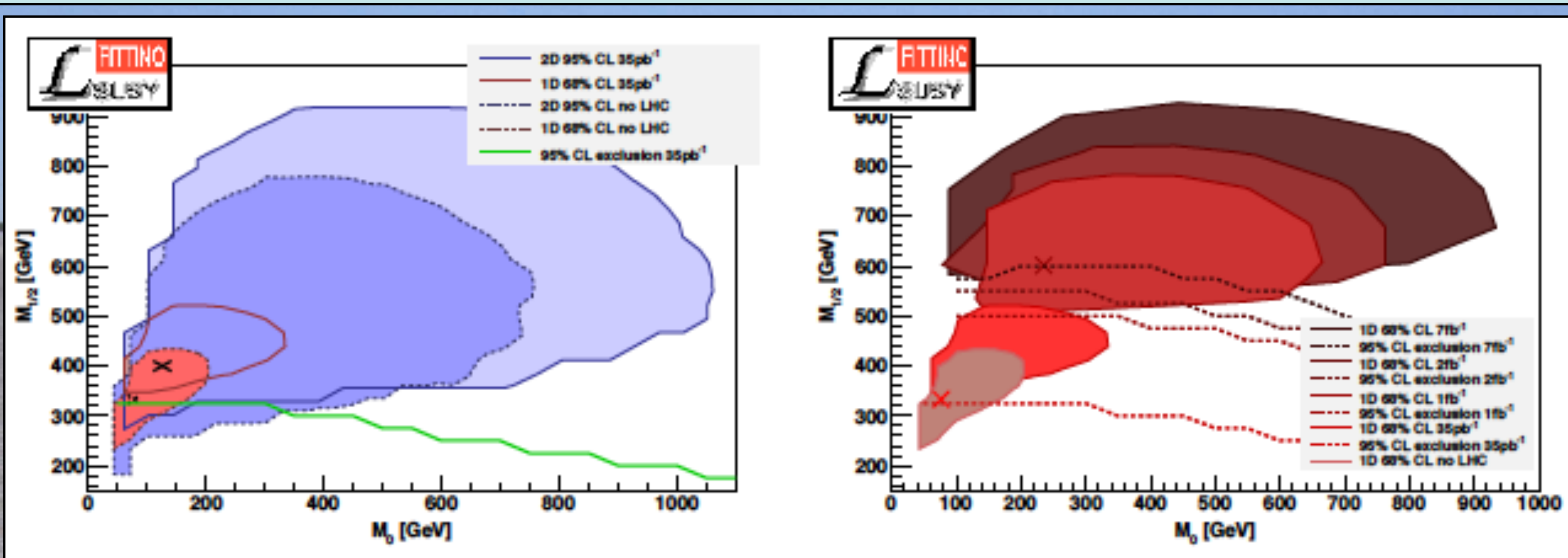
After LHC 2010

Detailed modelling of experimental likelihood

… no sign of the fixed-point region

KISMET: Allanach, Khoo, Lester & Williams

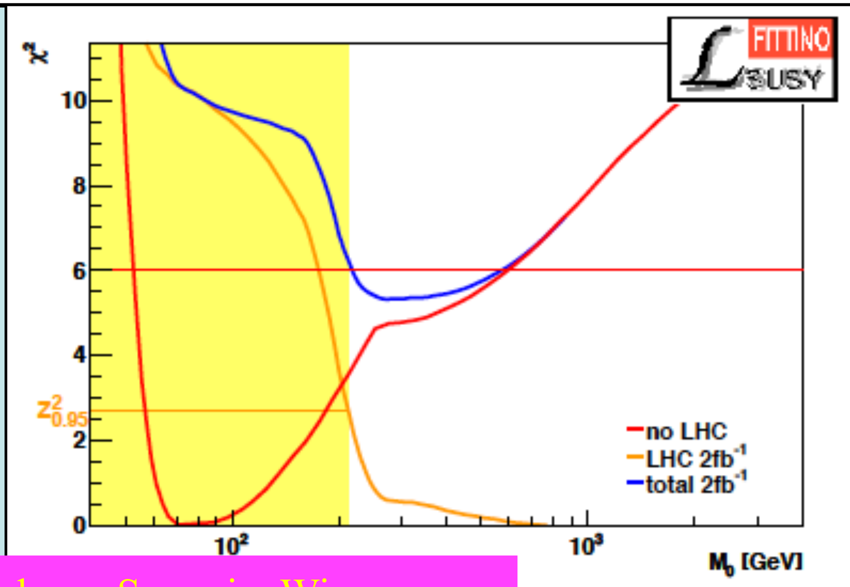
Pre-LHC vs Post-LHC



Uses MasterCode package

-LHC will push out in the ($m_{1/2}$, m_0) plane if no SUSY

-Illustration of possible pre/post-LHC tension $m_{1/2}$



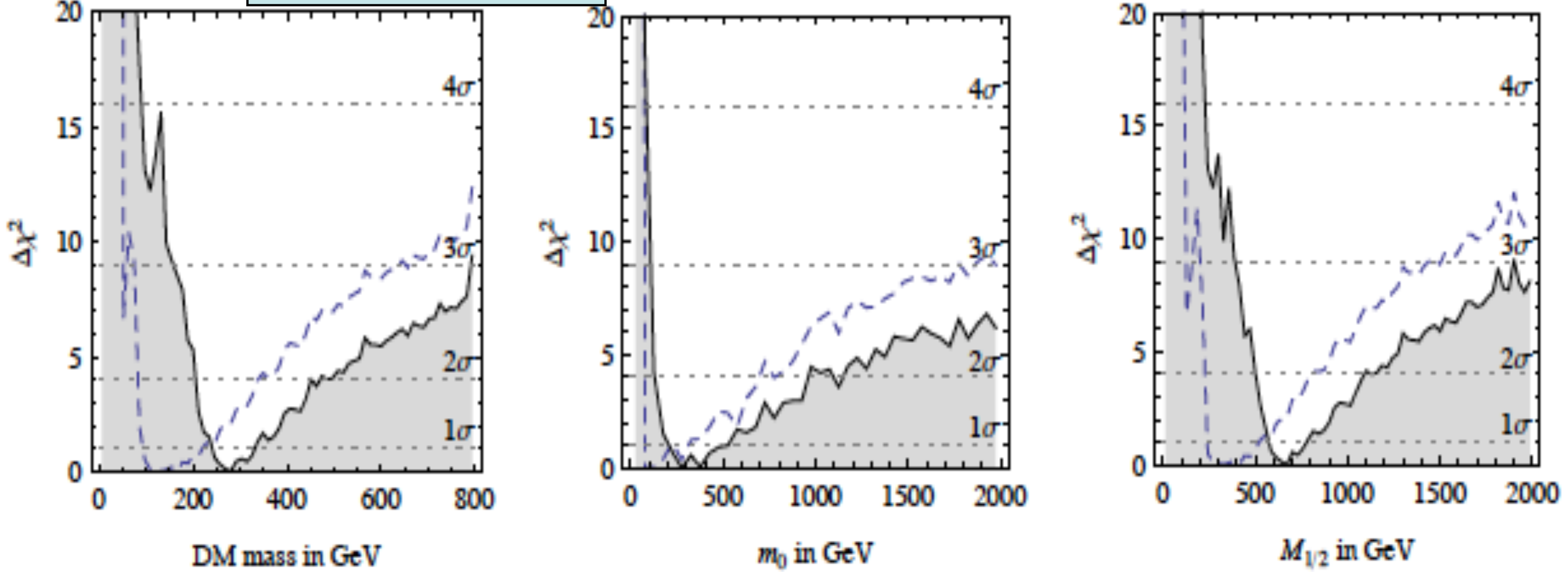
Fittino: Bechtle, Desch, Dreiner, Kramer, O'Leary, Robens, Sarrazin, Wienemann

Including XENON100

quantity	experiment	Standard Model
$\alpha_3(M_Z)$ [45]	0.1184 ± 0.0007	parameter
m_t [46]	173.1 ± 0.9	parameter
m_b [47]	4.19 ± 0.12	parameter
$\Omega_{\rm DM}h^2$ [48]	0.112 ± 0.0056	0
δg_μ [49]	$(2.8 \pm 0.8)10^{-9}$	0
$\text{BR}(B_d \to X_s\gamma)$ [50]	$(3.50 \pm 0.17)\,10^{-4}$	$(3.15 \pm 0.23)\,10^{-4}$
$\text{BR}(B_s \to \mu^+\mu^-)$ [19]	$(0.9 \pm 0.6)\,10^{-8}$	$(0.33 \pm 0.03)\,10^{-8}$
$\text{BR}(B_u \to \tau\bar{\nu})/\text{SM}$ [51]	1.25 ± 0.40	1

The data we fit, together with LHC and XENON100 bounds.

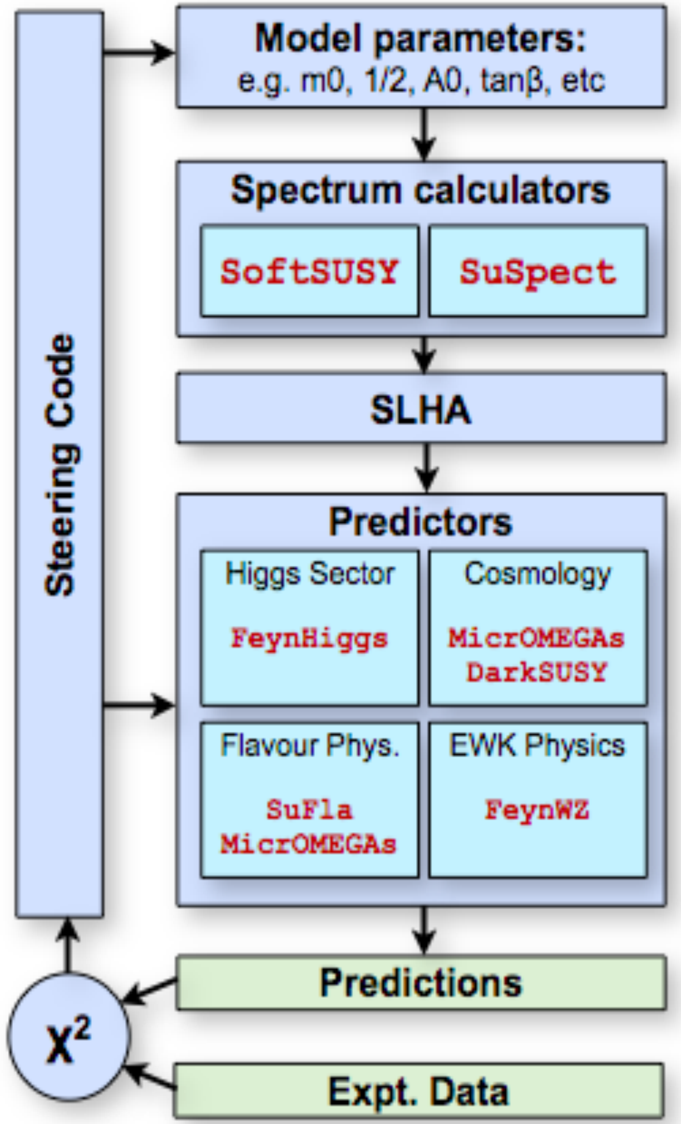
200,000 points



Farina, Kadastik, Pappadopulo, Pata, Raidal, Strumia

MasterCode

- **Combines diverse set of tools**
  - different codes : all state-of-the-art
    - Electroweak Precision (FeynWZ)
    - Flavour (SuFla, micrOMEGAs)
    - Cold Dark Matter (DarkSUSY, micrOMEGAs)
    - Other low energy (FeynHiggs)
    - Higgs (FeynHiggs)
  - different precisions (one-loop, two-loop, etc)
  - different languages (Fortran, C++, English, German, Italian, etc)
  - different people (theorists, experimentalists)
- **Compatibility is crucial! Ensured by**
  - close collaboration of tools authors
  - standard interfaces



O. Buchmueller, R. Cavanaugh, D. Colling, A. de Roeck, M.J. Dolan, J.R. Ellis, H. Flaecher, S. Heinemeyer, G. Isidori, D. Martinez Santos, K.A. Olive, S. Rogerson, F.J. Ronga, G. Weiglein

Constructing the χ^2

$$\chi^2 = \sum_i^N \frac{(C_i - P_i)^2}{\sigma(C_i)^2 + \sigma(P_i)^2} + \sum_i^M \frac{\left(f_{\mathrm{SM}_i}^{\mathrm{obs}} - f_{\mathrm{SM}_i}^{\mathrm{fit}}\right)^2}{\sigma(f_{\mathrm{SM}_i})^2}$$

$$+ \chi^2(b \to s\gamma) + \chi^2(g_\mu - 2) + \chi^2(\Omega h^2) + \chi^2(m_h)$$

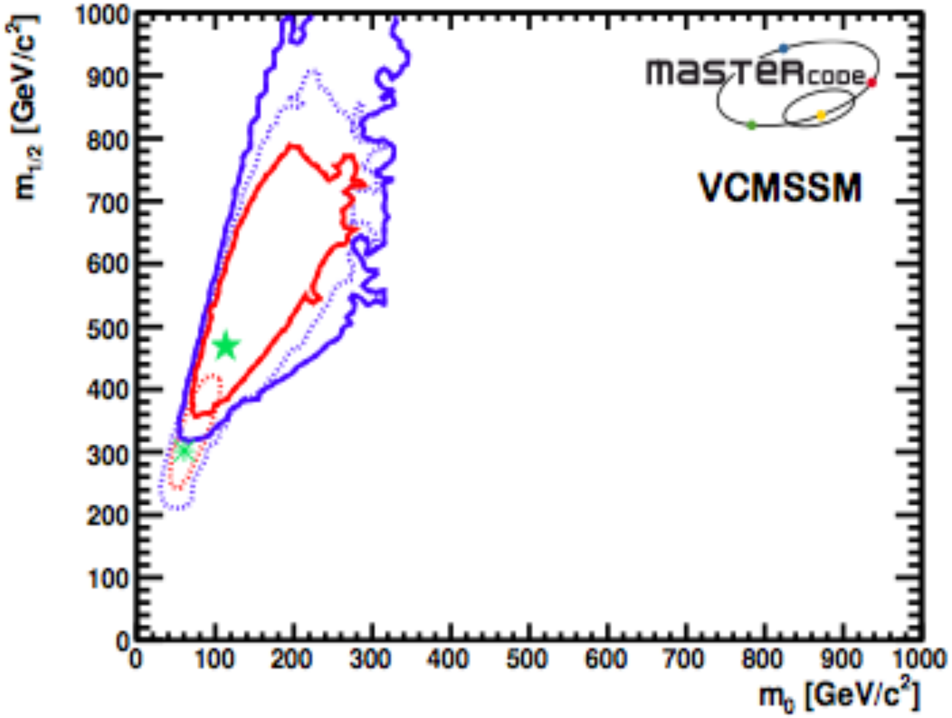
$$+ \chi^2(\mathrm{BR}(B_s \to \mu\mu)) + \chi^2(\mathrm{LHC}) + \chi^2(\mathrm{XENON100})$$

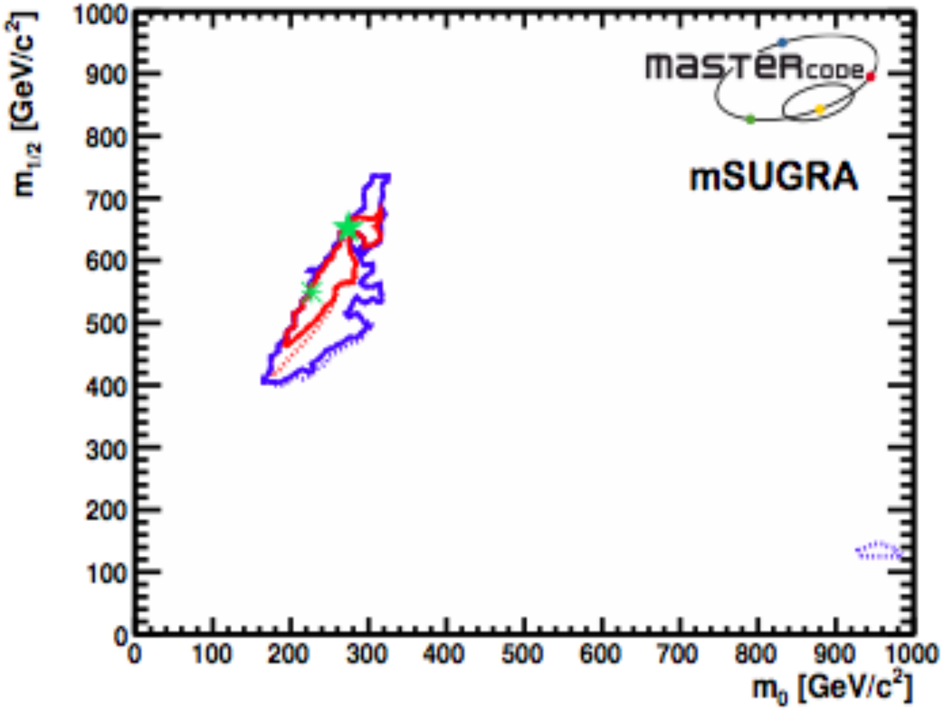
Recent Experimental Data!

- **Fit Methods (globally over all model parameters!)**
  - **Markov Chain Monte Carlo (MCMC)**
    - Actually used as a mere sampling method (sampling density not used)
    - success and failure of the steps defined by the χ^2
  - **χ^2 fit: `Minuit` minimisation**
    - used for "scans" or in conjunction with MCMCs to get overall best minimum
- **Afterburners**
  - **χ^2 terms additive → effects therefore also additive**
  - **Study effect of "interesting" (g-2, b→sγ, Ωh^2, etc) observables!**
    - sample space without "interesting" terms → larger, more general sampling
    - a posteriori add "interesting" terms after general sampling
    - Only need to sample multi-d space once! Enormous cost savings to due RGEs

Post-LHC, Post-XENON100

2010 ATLAS + CMS with 36 pb^{-1} of LHC Data





VCMSSM

60 million points sampled

mSUGRA

60 million points sampled

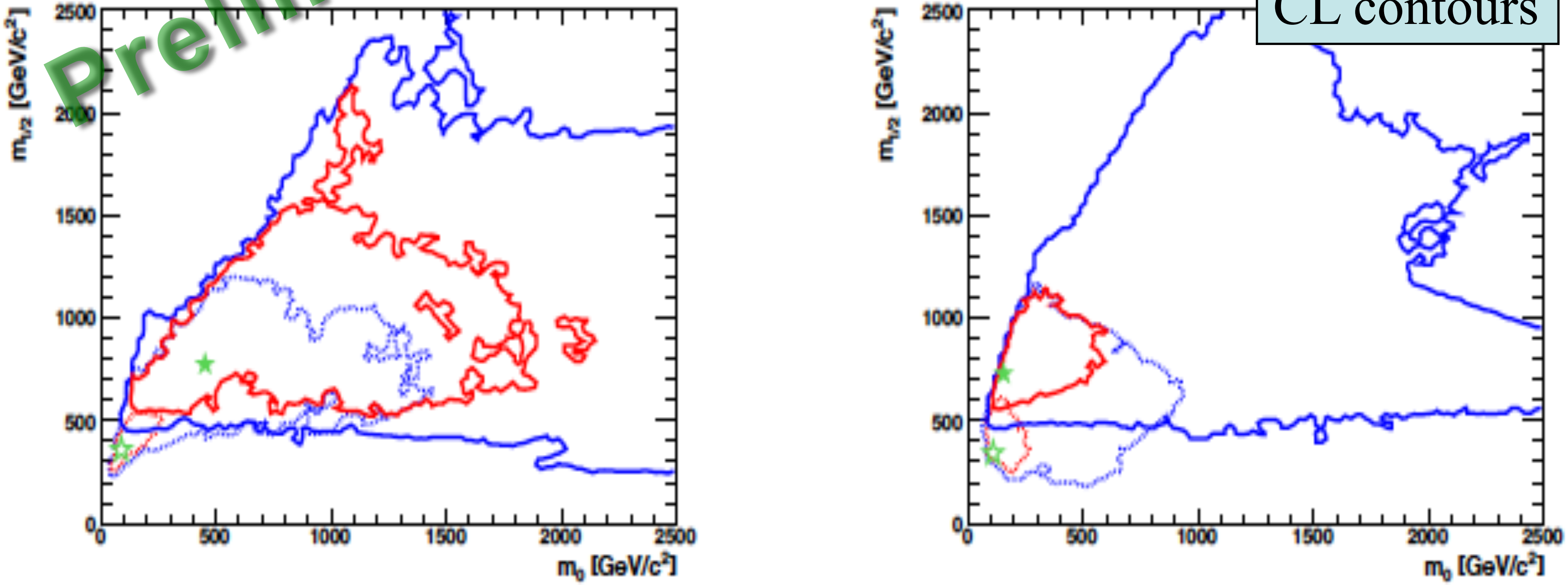
Model	Min χ^2	Prob	$m_{1/2}$	m_0	A_0	$\tan\beta$
VCMSSM	22.5	31%	300	60	30	9
post-LHC/XENON100	27.1	13%	390	90	70	11
mSUGRA	29.4	6.1%	550	230	430	28
post-LHC/XENON100	30.9	5.7%	550	230	430	28

Post-LHC, Post-XENON100

Preliminary

2011 ATLAS + CMS with 1 fb^{-1} of LHC Data

68% & 95% CL contours



CMSSM
60 million points sampled

NUHM1
70 million points sampled

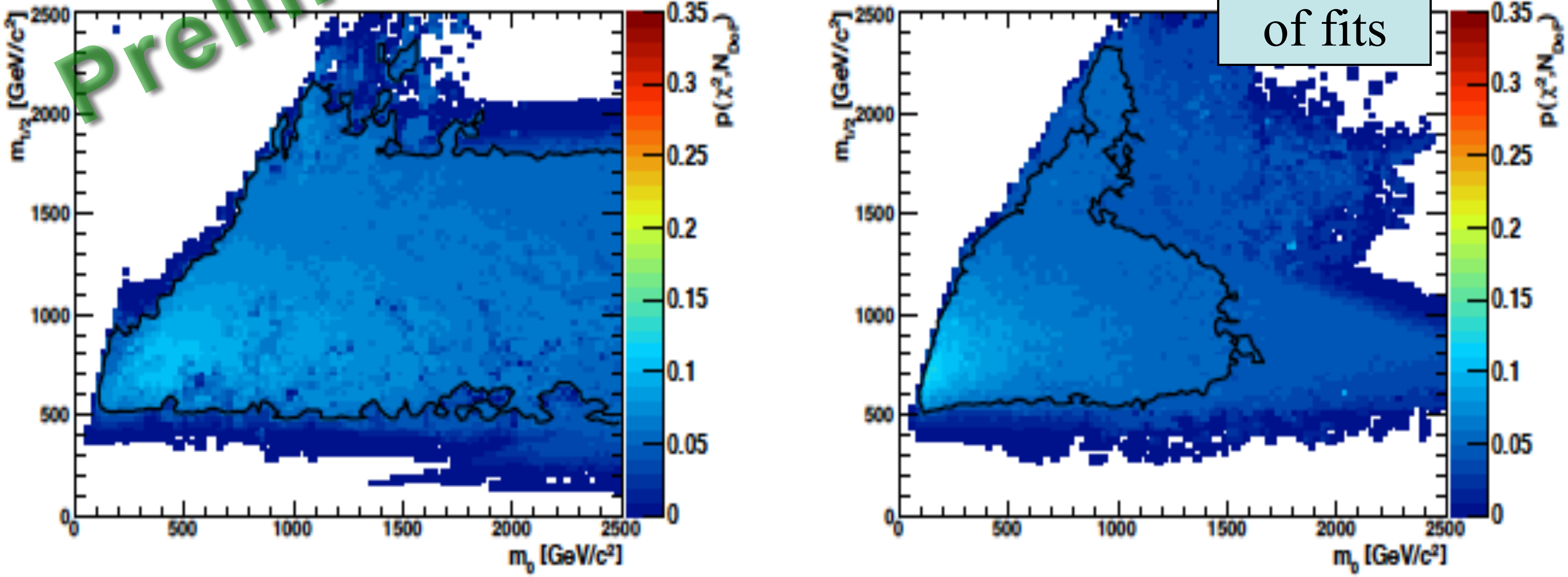
Red and blue curves represent $\Delta\chi^2$ from global minimum, located at ☆

Preferred region "opens up" at cost of worsening global χ^2 value!

Post-LHC, Post-XENON100

Preliminary

2011 ATLAS + CMS with 1 fb^{-1} of LHC Data



Model	Min χ^2	Prob	$m_{1/2}$	m_0	A_0	$\tan\beta$
CMSSM	22.5	26%	310	60	-60	10
post-LHC/XENON100	29.3	11%	730	420	-1100	40
NUHM1	20.5	25%	310	60	-60	10
post-LHC/XENON100	27.3	13%	690	160	-880	33

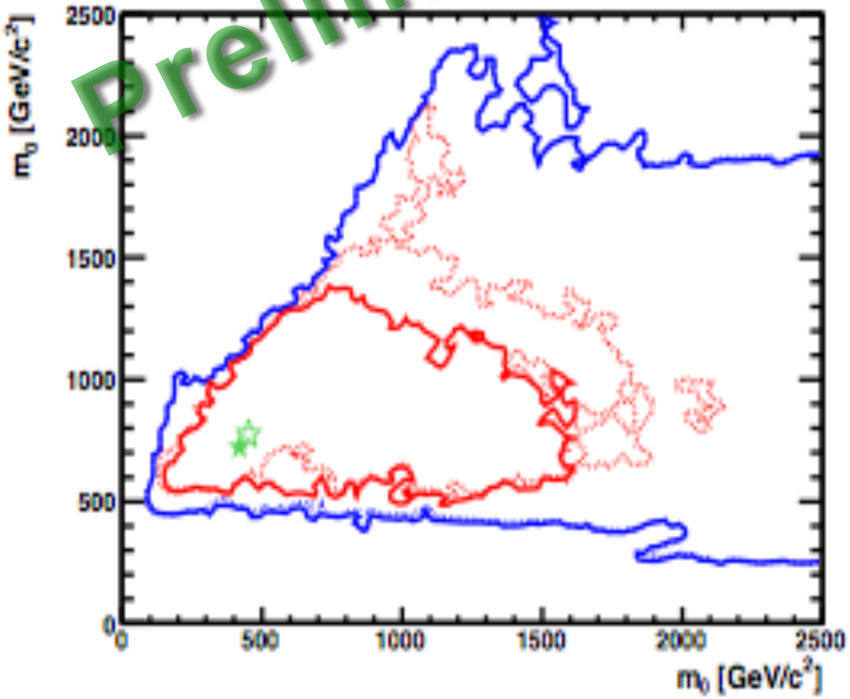
With 1 fb^{-1}: CMSSM and NUHM1 still above 10% CL

VCMSSM and mSUGRA now less than 5% CL

Post-LHC, Post-XENON100

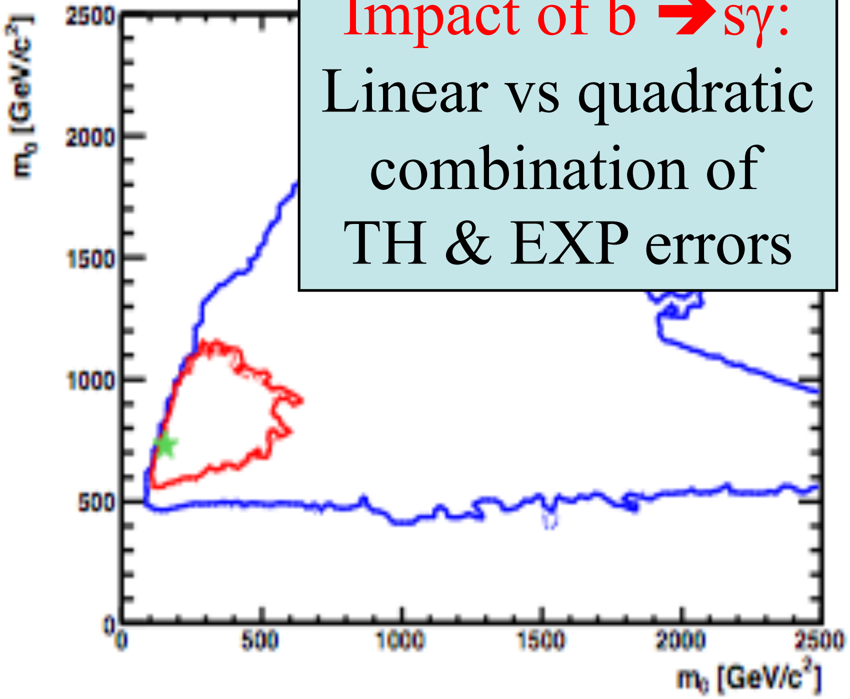
Preliminary

2011 ATLAS + CMS with 1 fb^{-1} of LHC Data



CMSSM

60 million points sampled



Impact of b ➔sγ:
Linear vs quadratic combination of TH & EXP errors

NUHM1

70 million points sampled

Red and blue curves represent $\Delta\chi^2$ from global minimum, located at ☆

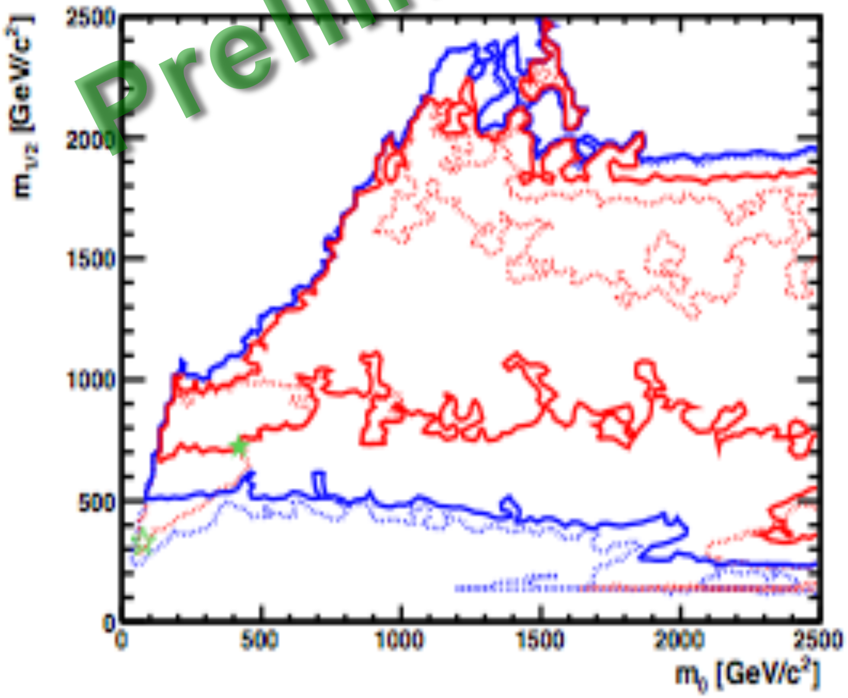
More conservative linear combination improves global χ2, contracts 68% CL region

Post-LHC, Post-XENON100

Preliminary

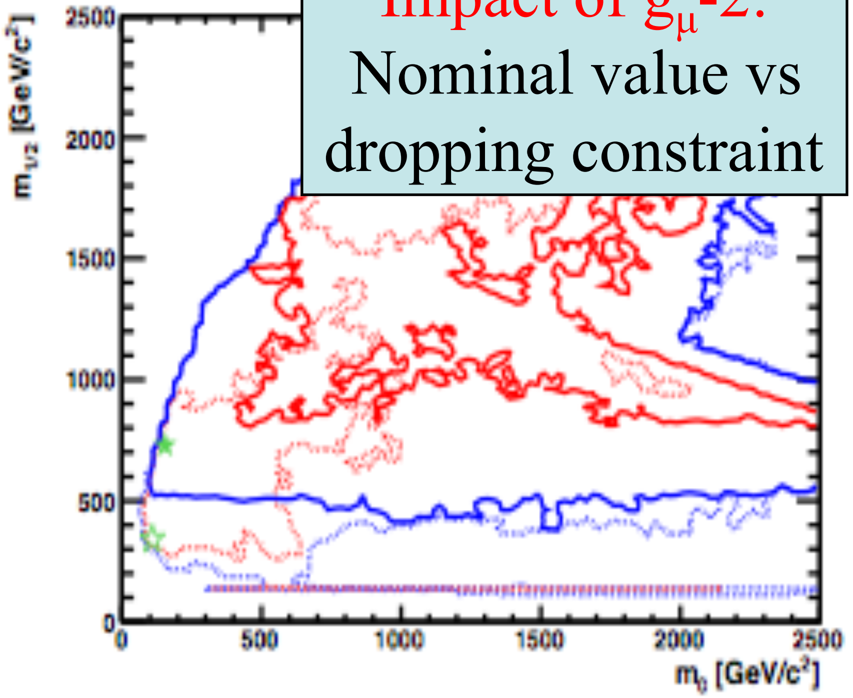
2011 ATLAS + CMS with 1 fb^{-1} of LHC Data

Impact of g_μ-2:
Nominal value vs dropping constraint



CMSSM

60 million points sampled



NUHM1

70 million points sampled

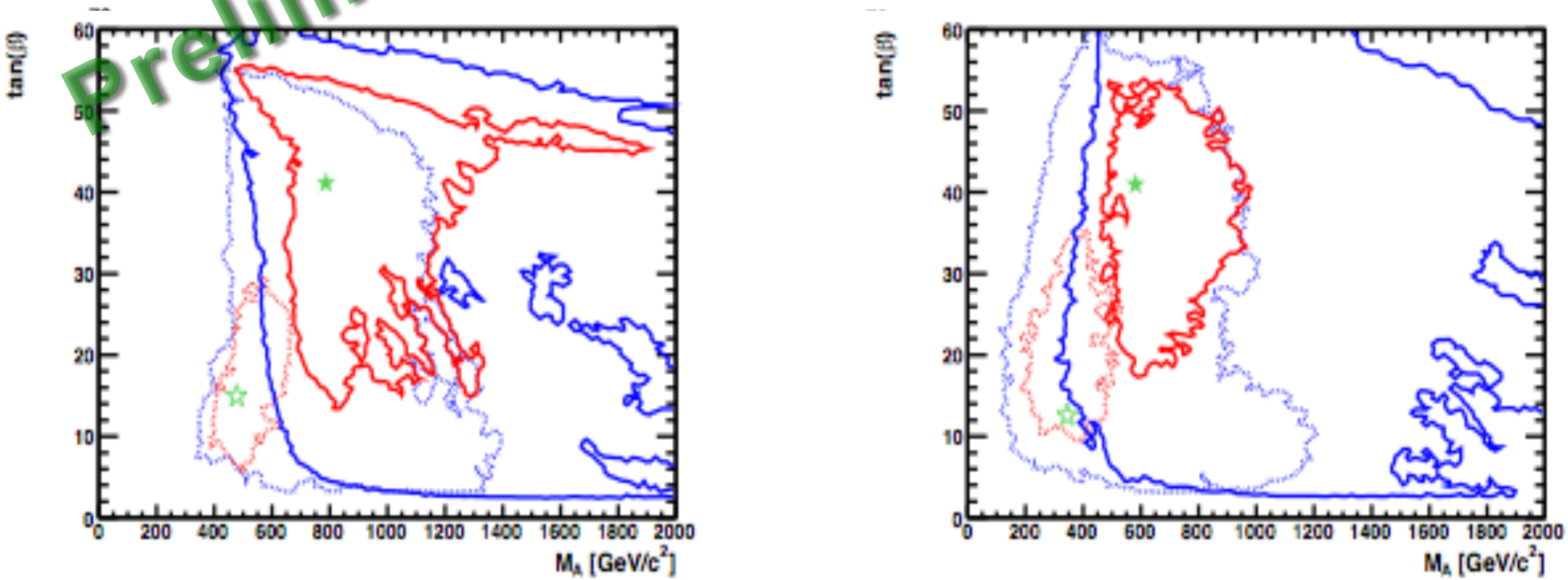
Red and blue curves represent $\Delta\chi^2$ from global minimum, located at ☆

Dropping g_μ - 2 allows masses up to dark matter limit

Post-LHC, Post-XENON100

Preliminary

2011 ATLAS + CMS with 1 fb^{-1} of LHC Data



CMSSM
60 million points sampled

NUHM1
70 million points sampled

Red and blue curves represent $\Delta\chi^2$ from global minimum, located at ☆

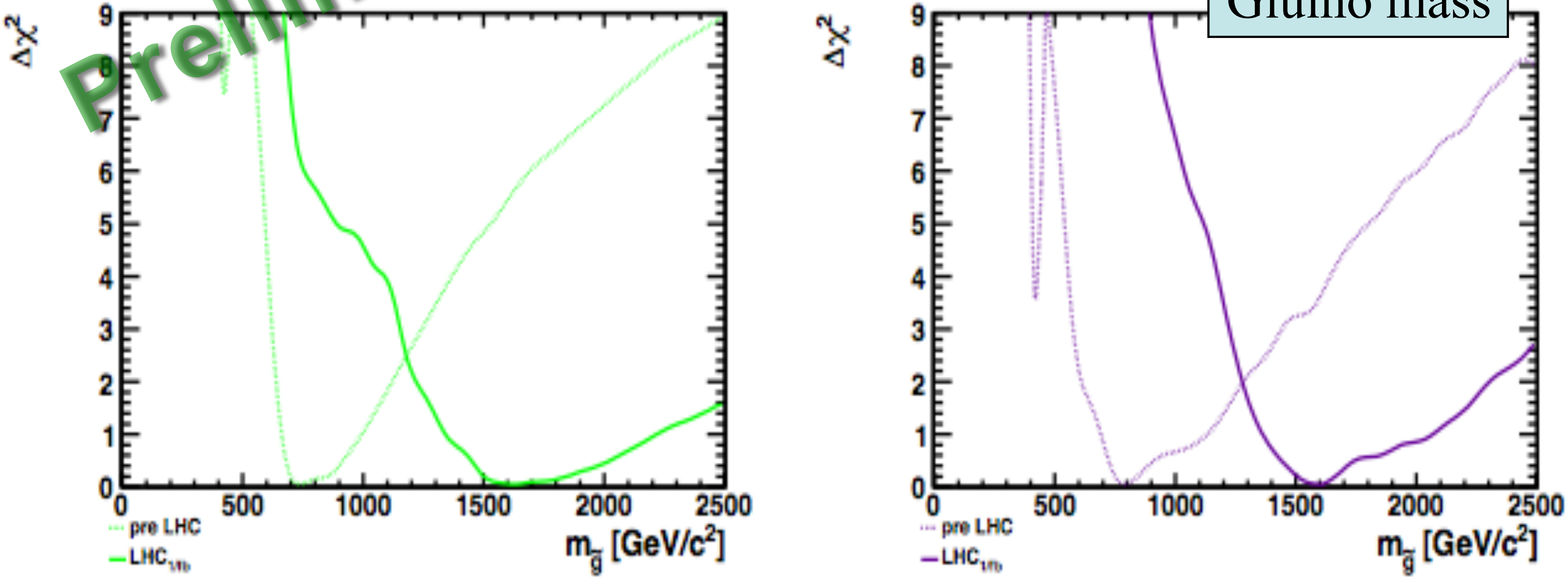
Preferred region "opens up" at cost of worsening global χ^2 value!

Post-LHC, Post-XENON100

2011 ATLAS + CMS with 1 fb^{-1} of LHC Data

Preliminary

Gluino mass



CMSSM

60 million points sampled

NUHM1

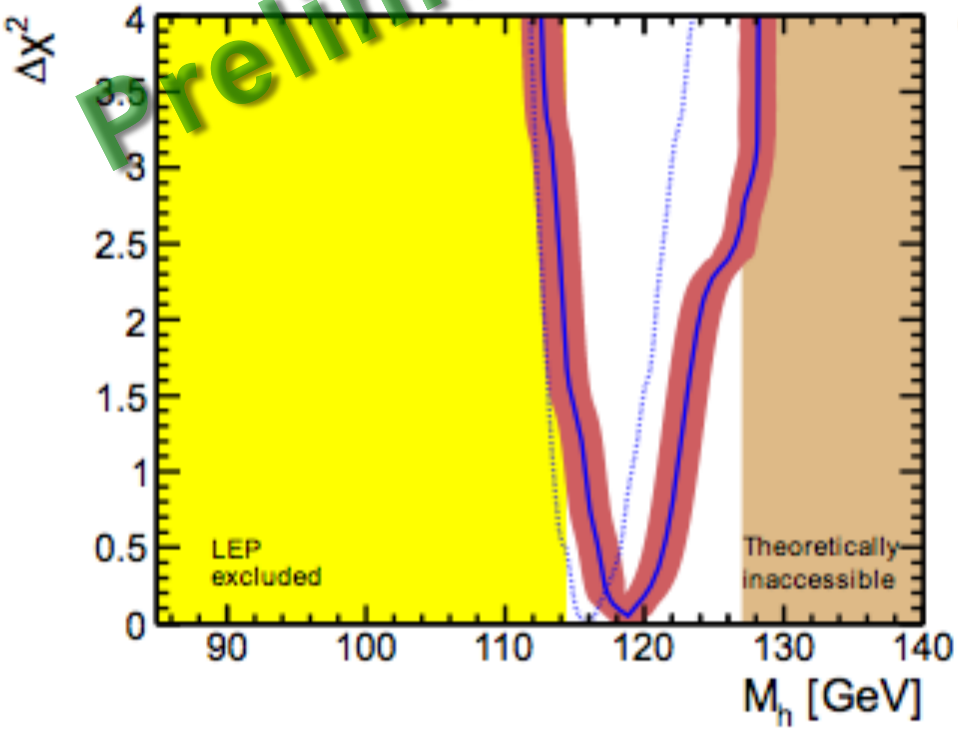
70 million points sampled

Favoured values of gluino mass significantly above pre-LHC, > 1 TeV

Post-LHC, Post-XENON100

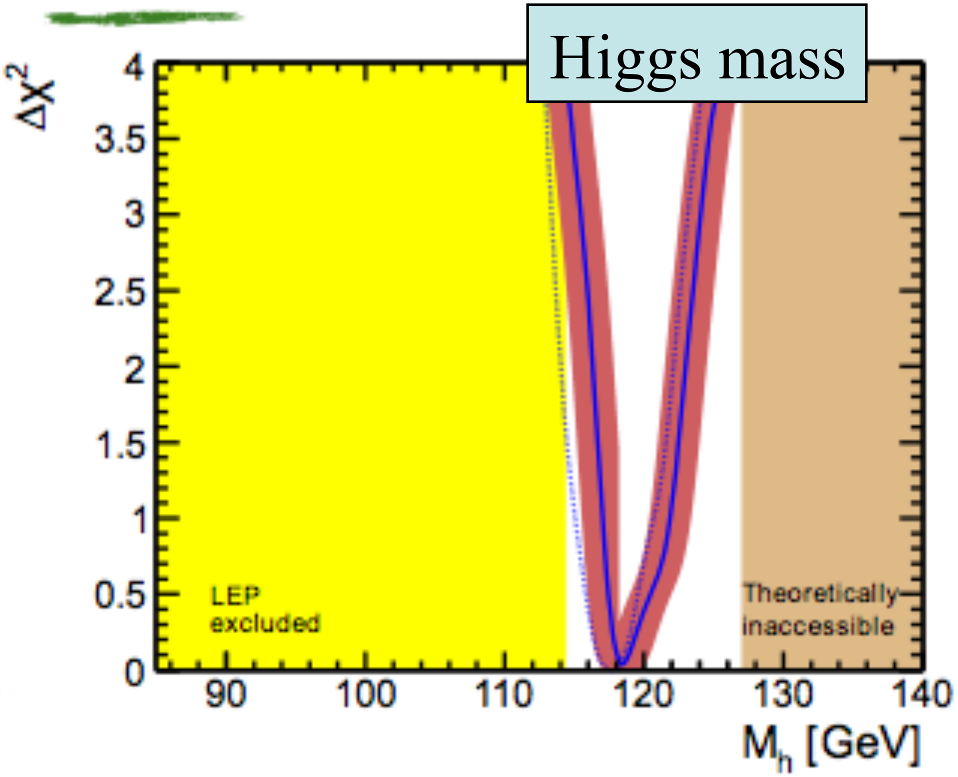
2011 ATLAS + CMS with 1 fb^{-1} of LHC Data

Preliminary



CMSSM

60 million points sampled

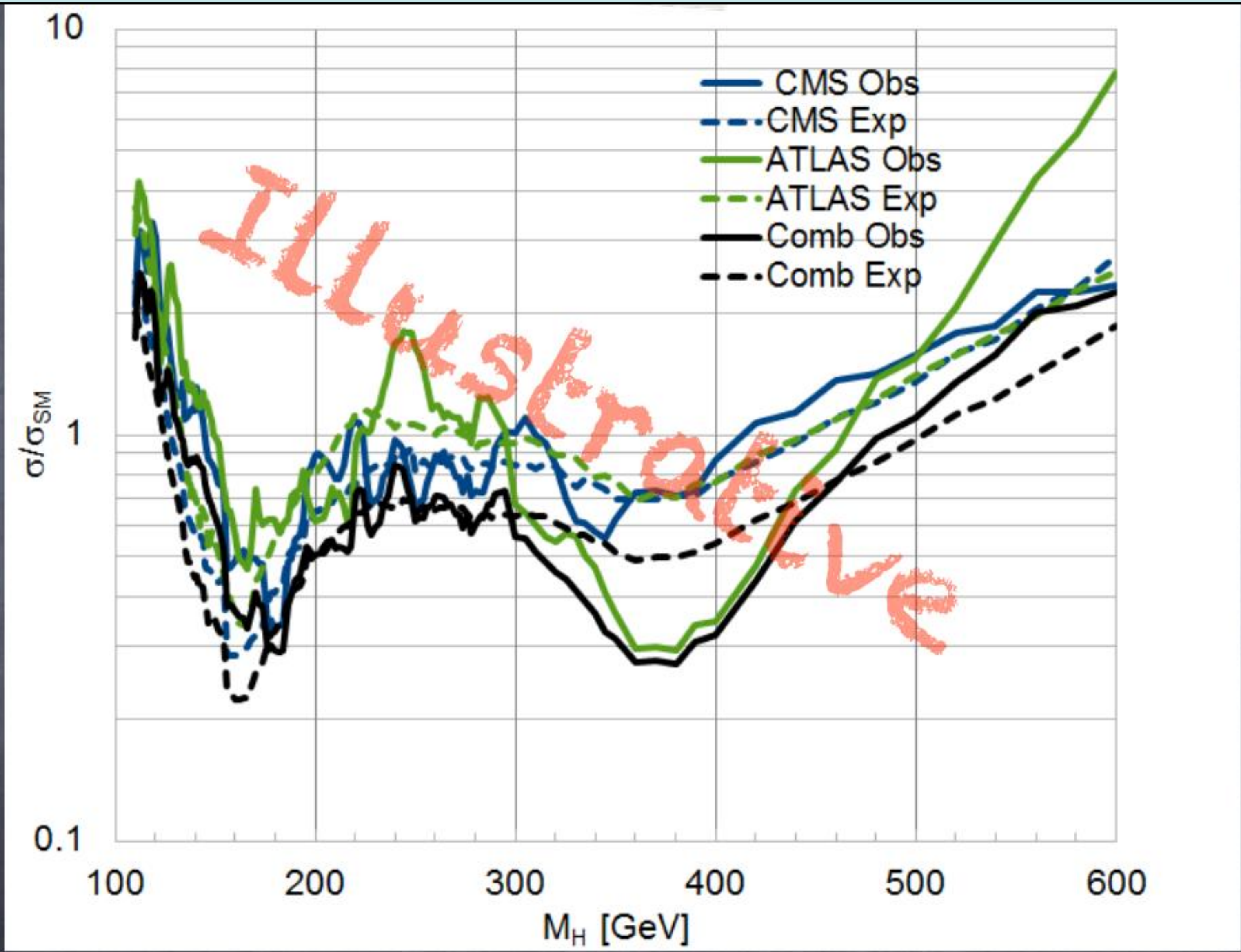


NUHM1

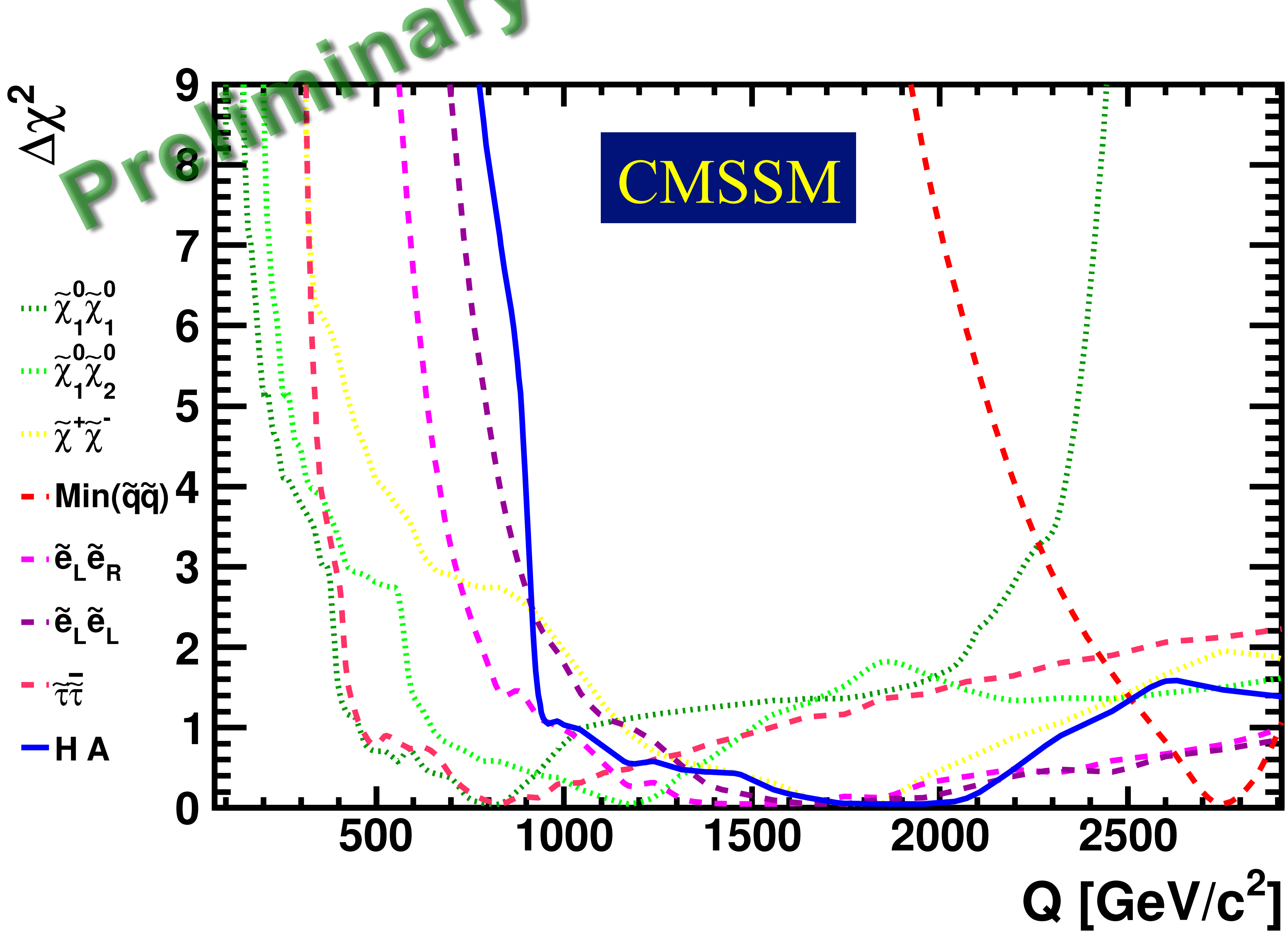
70 million points sampled

Favoured values of Mh ~ 119 GeV:
Coincides with value consistent with LHC !

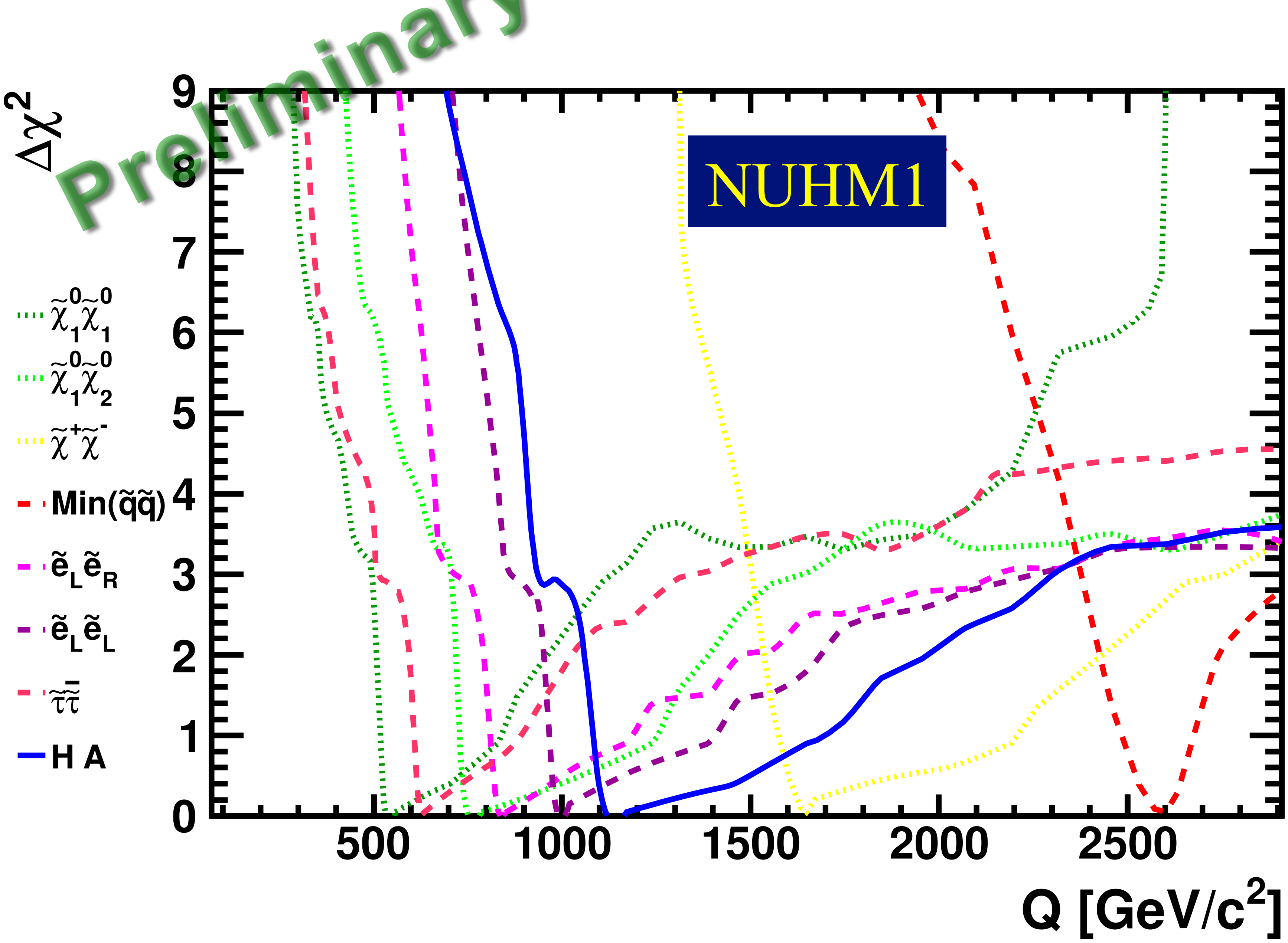
The Higgs can run, but it cannot hide !



Likelihoods for sparticle thresholds



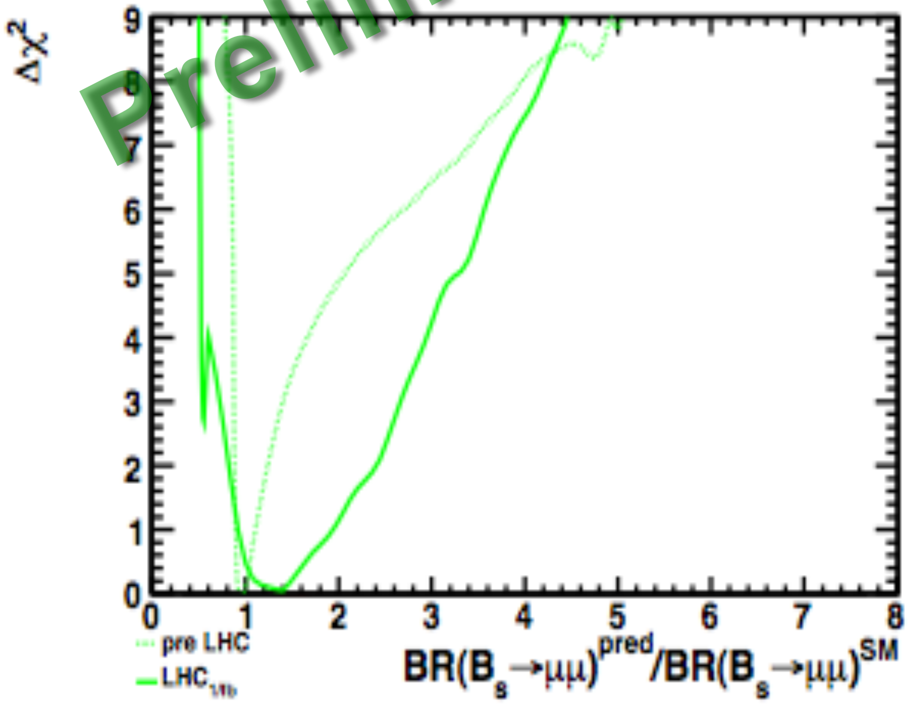
Likelihoods for sparticle thresholds

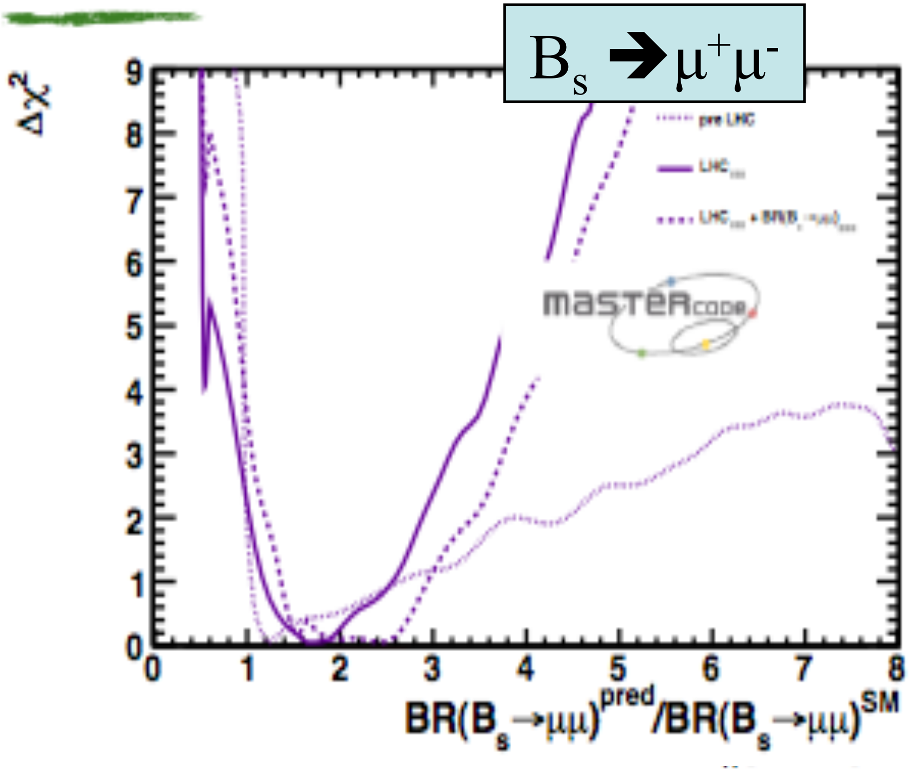


Post-LHC, Post-XENON100

Preliminary

2011 ATLAS + CMS with 1 fb^{-1} of LHC Data





CMSSM

60 million points sampled

NUHM1

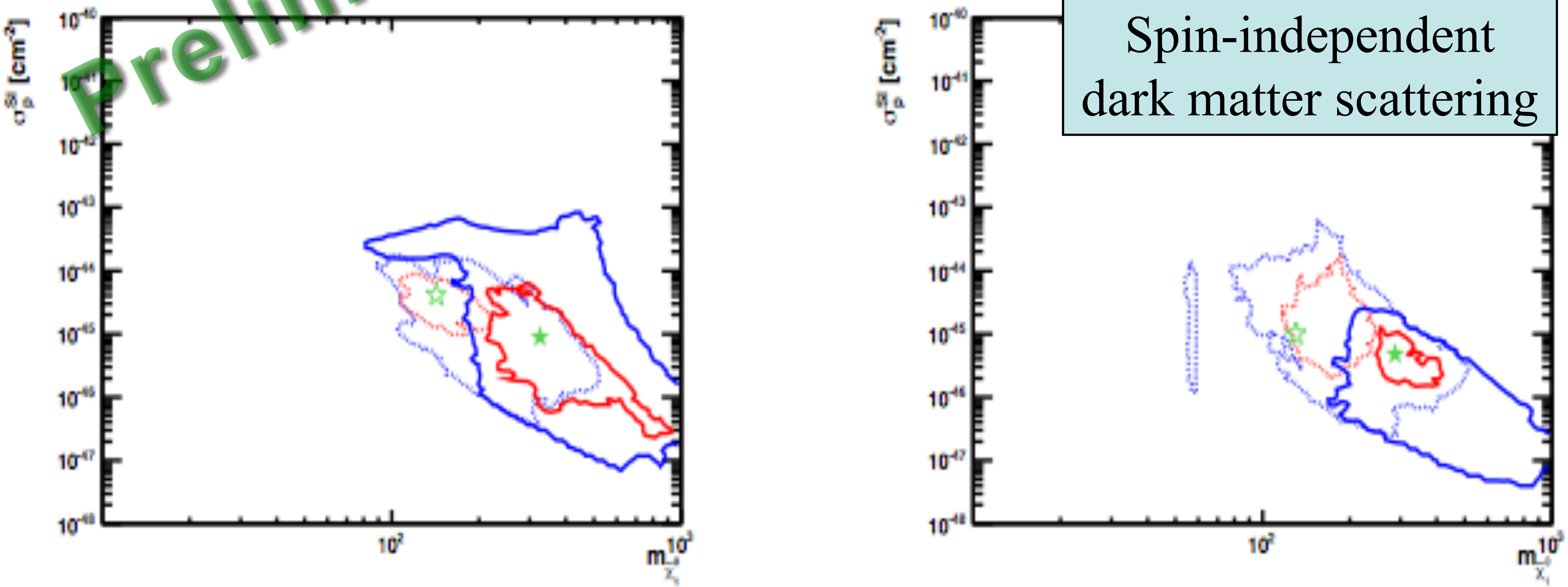
70 million points sampled

Favoured values of $BR(B_s \rightarrow \mu^+\mu^-)$ above SM value !

Post-LHC, Post-XENON100

Preliminary

2011 ATLAS + CMS with 1 fb^{-1} of LHC Data



Spin-independent dark matter scattering

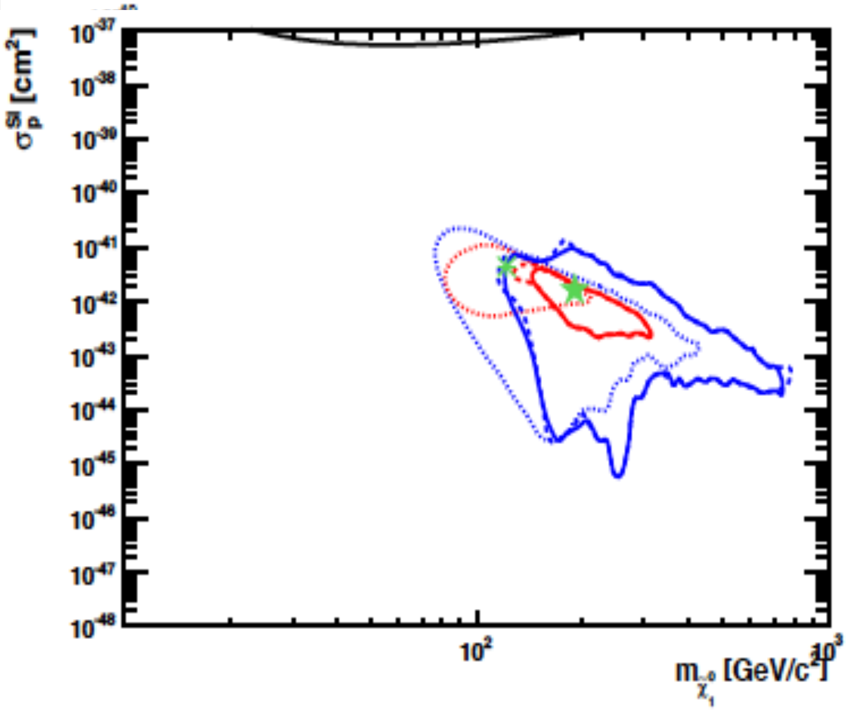
CMSSM
60 million points sampled

NUHM1
70 million points sampled

Significant impact of XENON100 experiment:
Prospects for coming years !

Post-LHC, Post-XENON100

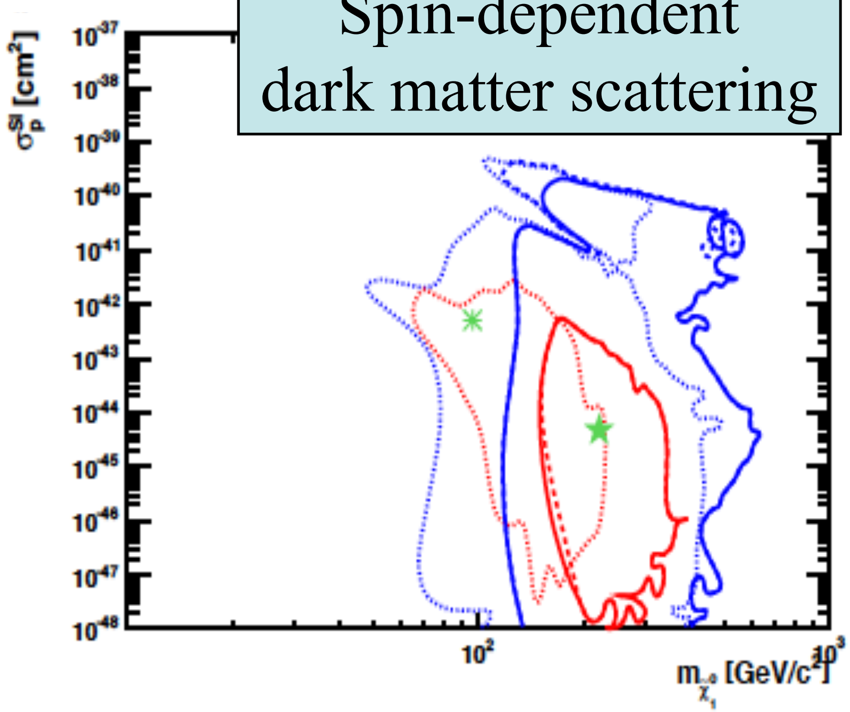
2010 ATLAS + CMS with 35pb^{-1} LHC Data



CMSSM

60 million points sampled

Spin-dependent dark matter scattering



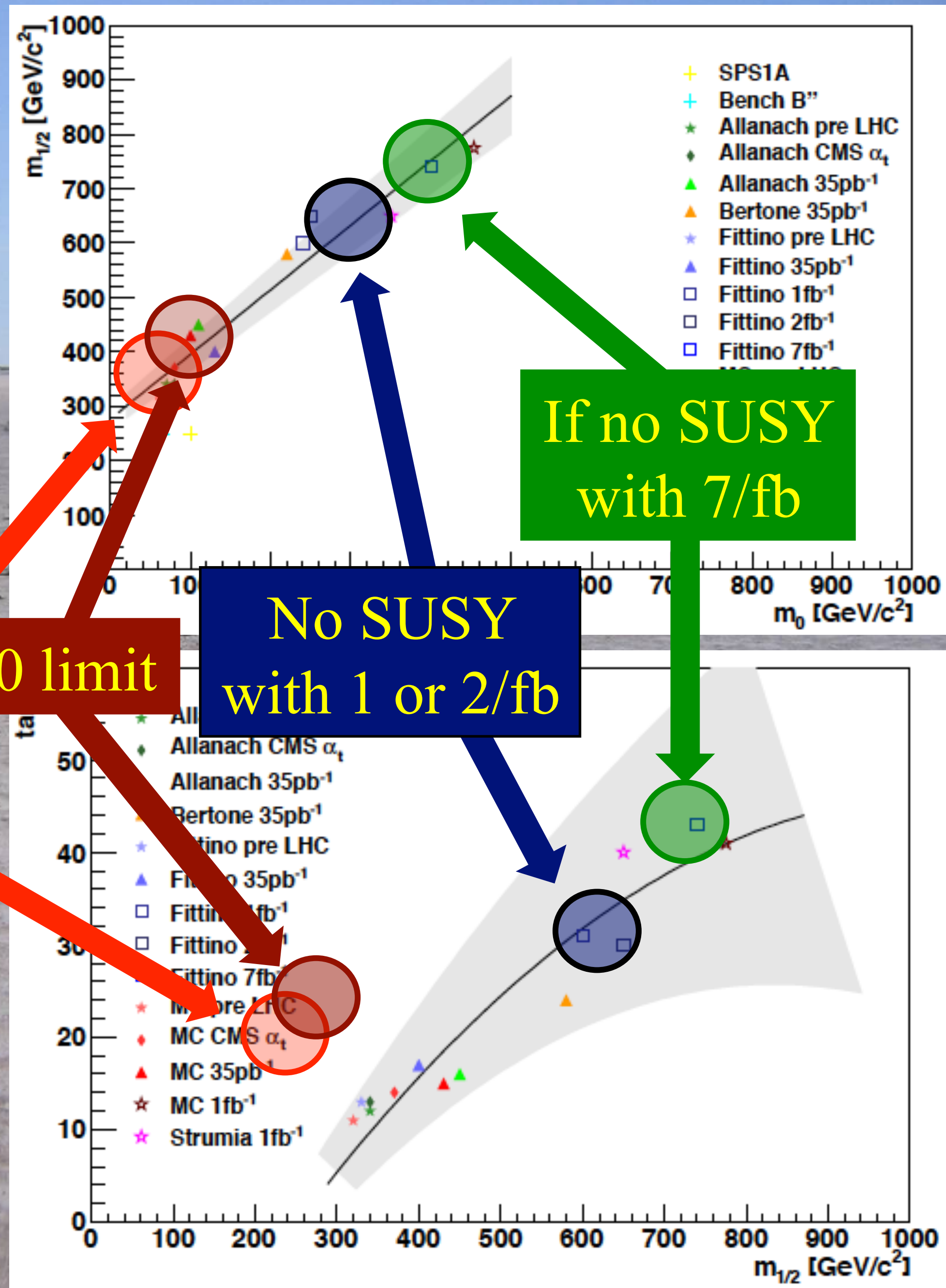
NUHM1

70 million points sampled

Much further below prospective experimental sensitivity ?

Trajectory of CMSSM Fits

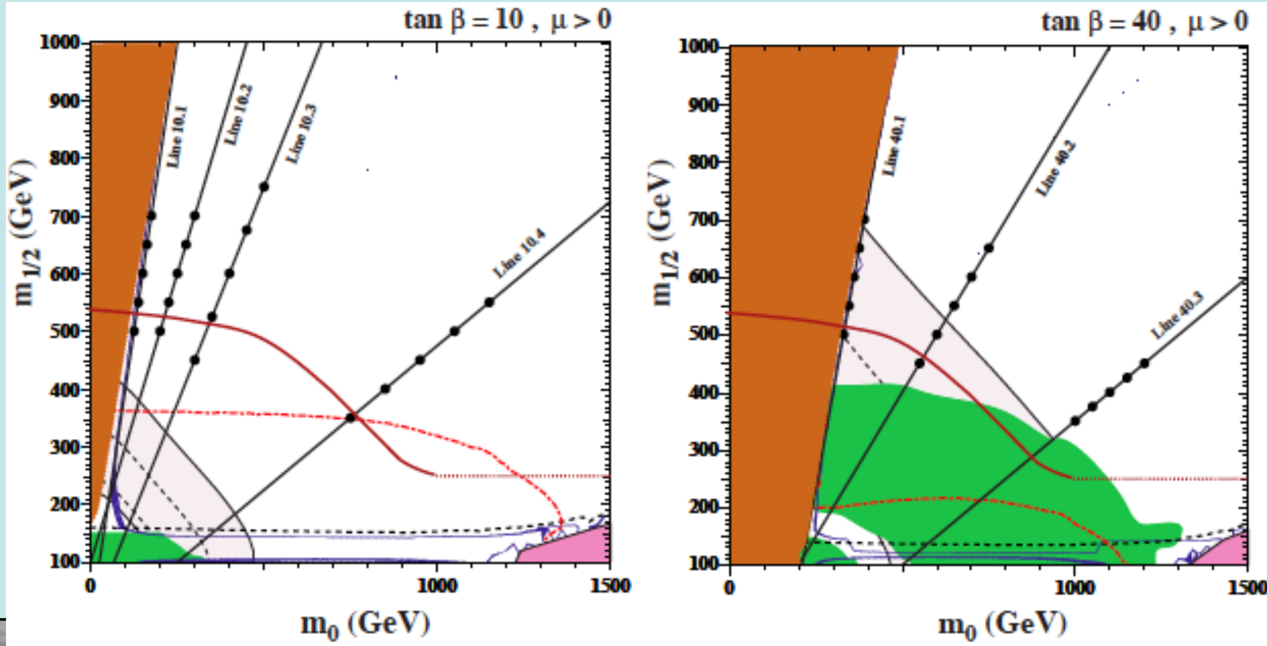
How have best-fit CMSSM points evolved?
How would they evolve if SUSY is not discovered in 2011/2?



- ✚ Old benchmarks
- ★ Pre-LHC fits
- ▲ After LHC 2010
- ■ After LHC 2011?

'Sustainable' Benchmarks

- Many models: CMSSM, NUHM1, RPV-CMSSM, mGMSB, mAMSB, MM-AMSB and pMSSM, NMSSM
- Benchmark planes, lines & points, e.g., CMSSM
  - Varied signatures, similar along lines, move up as needed



AbdusSalam, Allanach, Dreiner, Ellis, Ellwanger, Gunion, Heinemeyer, Krämer, Mangano, Olive, Rogerson, Roszkowski, Schlaffer, Weiglein

Summary & Perspectives

- LHC data putting pressure on popular models
- Theorists want to combine various constraints
  - Seek to construct global likelihood function
  - Tension between LHC and $g_\mu - 2$
  - Mitigated at larger tan β
- **Need more information than 95% CL**
- **Desirable to improve TH-EXP dialogue**
- Need to extend studies to other models
  - Compressed spectra, RPV, …