TeV Scale SUSY – What Now?

Leszek Roszkowski*

National Centre for Nuclear Research (NCNR/NCBJ)

Warsaw, Poland

(BayesFITS group)

*On leave of absence from University of Sheffield

INNOVATIVE ECONOMY
NATIONAL COHESION STRATEGY

FNP
Foundation for Polish Science

EUROPEAN UNION
EUROPEAN REGIONAL DEVELOPMENT FUND

Grants for innovation. Project operated within the Foundation for Polish Science "WELCOME" co-financed by the European Regional Development Fund

BayesFITS Group in Warsaw

- **New research group at National Centre for Nuclear Research, formed in mid-2011**
- **Funded by a 4.5-yr grant (~1.5MEuro) from Foundation for Polish Science**
- **Currently four postdocs, 1 PhD student, plus several local and external collaborators**

LR

Shoaib Munir

Enrico Sessolo

Sming Tsai

Kamila Kowalska

Sebastian Trojanowski

- **So far 9 papers out, 6 published or accepted (PRD, JHEP), more in pipeline**
- **Research area:**
  - **``new physics'' (SUSY) and astroparticle physics (dark matter) in the LHC era**
  - **Early Universe, relics, etc**
  - **Flavor physics, …**

Outline

- ✧ Why TeV-scale for SUSY
- ✧ How to compare theory with data
- ✧ Implications of mh~126 GeV for favored SUSY mass scale
- ✧ Impact of DM relic abundance and searches
- ✧ CMSSM and beyond (CNMSSM, MSSM)
- ✧ Summary

Based on:

- **Two ultimate tests of constrained SUSY, 1302.5956**
- **The Constrained NMSSM with a 125 GeV Higgs boson -- A global analysis, 1211.1693**
- **Di-photon rate enhancement in the NMSSM with nearly degenerate scalar and pseudoscalar Higgs bosons, 1305.0591**
- **Constrained MSSM favoring new territories: The impact of new LHC limits and a 125 GeV Higgs boson, 1206.0264**

…with updates

Where is SUSY?

After LHC(7/8TeV):

We know better now where SUSY is not.

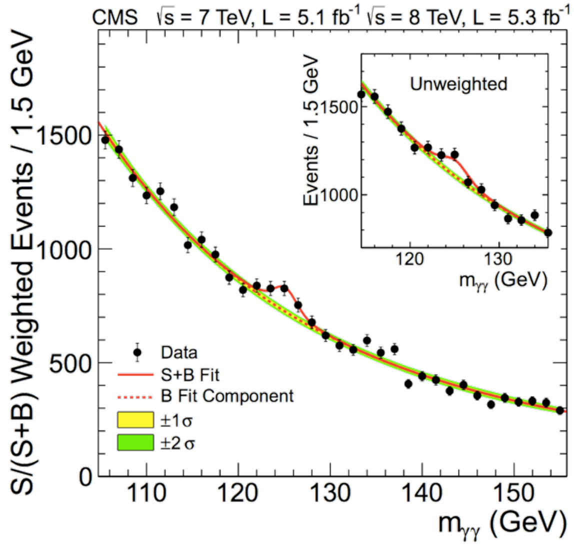
Hints where SUSY may actually be.

© Ron Leishman * www.ClipartOf.com/1047187

BSM: hints from the LHC….

Main news from the LHC so far…

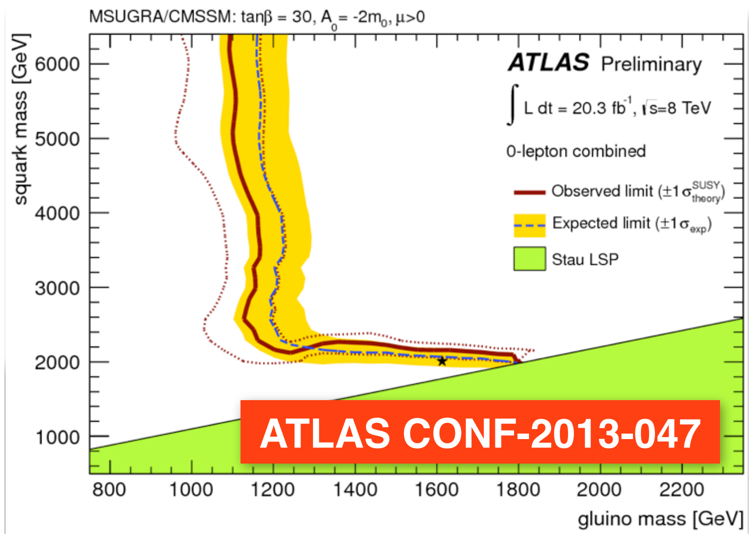
- **Higgs(-like) particle at ~126 GeV**



- **No (convincing) deviations from the SM**

$$\mathrm{BR}(\overline{B}_s \to \mu^+\mu^-) = \left(3.2^{+1.5}_{-1.2}\right) \times 10^{-9}$$

- **Stringent lower limits on superparner masses**



SUSY masses reaching 1 TeV scale+…

…and from the media…

Is Supersymmetry Dead?

The grand scheme, a stepping-stone to string theory, is still high on physicists' wish lists. But if no solid evidence surfaces soon, it could begin to have a serious PR problem

SCIENTIFIC AMERICAN™

April 2012

Nothing new…

315 Physicists Report Failure In Search for Supersymmetry

The negative result illustrates the risks of Big Science, and its often sparse pickings.

By MALCOLM W. BROWNE

Three hundred and fifteen physicists worked on the experiment.

Their apparatus included the Tevatron, the world's most powerful particle accelerator, as well as a $65 million detector weighing as much as a warship, an advanced new computing system and a host of other innovative gadgets.

But despite this arsenal of brains and technological brawn assembled at the Fermilab accelerator laboratory, the participants have failed to find their quarry, a disagreeable reminder that as science gets harder, even Herculean efforts do not guarantee success.

NEWS SCIENCE & ENVIRONMENT

Home | UK | Africa | Asia | Europe | Latin America | Mid-East | US & Canada | Business | Health | Sci/Environment

27 August 2011 Last updated at 06:41 GMT

7.4K Share

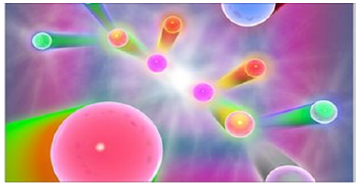
LHC results put supersymmetry theory 'on the spot'

By Pallab Ghosh
Science correspondent, BBC News

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

Researchers failed to find evidence of so-called "supersymmetric" particles, which many physicists had hoped would plug holes in the current theory.

Theorists working in the field have told BBC News that they may have to come up with a completely new idea.



Supersymmetry predicts the existence of mysterious super particles.

Data were presented at the Lepton Photon science meeting in Mumbai.

Related Stories

Energy, luminosity and the number of physicist failing to find SUSY have all increased by factor of 10...

CDF, ~2003

Constrained SUSY – still alive?

The constrained MSSM (CMSSM) paradigm is "hardly tenable"

At Open Symposium of the European Strategy Preparatory Group, Krakow, Poland, 10-12 Sept. 2012

Constrained SUSY is in coma

A. Masiero, PLANCK-13

Really?

Constrained SUSY – still alive?

The constrained MSSM (CMSSM) paradigm is "hardly tenable"

At Open Symposium of the European Strategy Preparatory Group, Krakow, Poland, 10-12 Sept. 2012

Conventional susy models (CMSSM, NMSSM, ….) do not work as such and should finally rest in peace

F. Zwirner, Moriond EW (2013) summary talk

Constrained SUSY is in coma

A. Masiero, PLANCK-13

Really?

My conjecture:

(Coined before LHC era.)

SUSY cannot be experimentally ruled out.

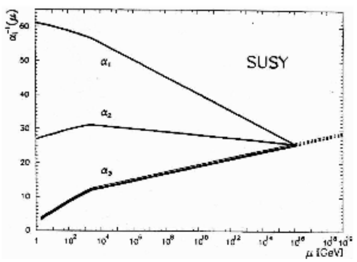
It can only be discovered.

Or else abandoned.

SUSY: Constrained or Not?

- <u>Constrained:</u>

Low-energy SUSY models with unification relations among gauge couplings and (soft) SUSY mass parameters



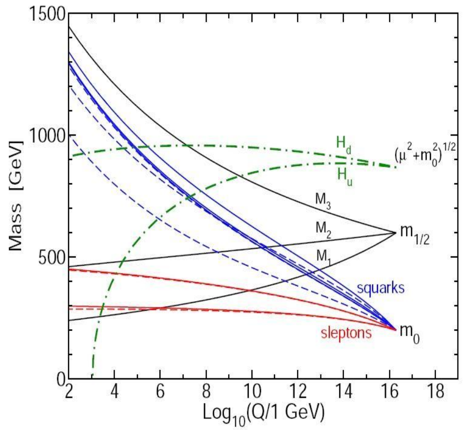


figure from hep-ph/9709356

<u>Virtues:</u>

- Well-motivated
- Predictive (few parameters)
- Realistic

Many models:

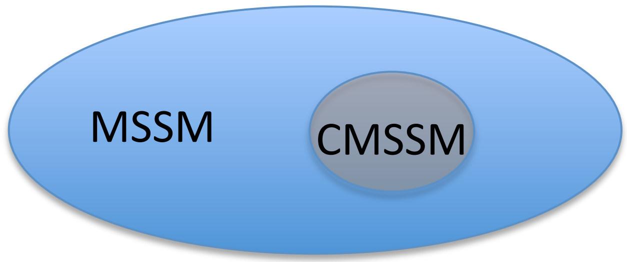
- CMSSM (Constrained MSSM): 4+1 parameters
- NUHM (Non-Universal Higgs Model): 6+1
- CNMSSM (Constrained Next-to-MSSM) 5+1
- CNMSSM-NUHM: 7+1
- String-inspired, split, ``natural'', etc

- <u>Phenomenological:</u>

Supersymmetrized SM…

Features:

- Many free parameters
- Broader than constrained SUSY



Many models:

- general MSSM – over 120 params
- MSSM + simplifying assumptions
- pMSSM: MSSM with 19 params
- p9MSSM, p12MSSM, pnMSSM, …

The 126 GeV SM-Like Higgs Boson

A blessing or a curse for SUSY?

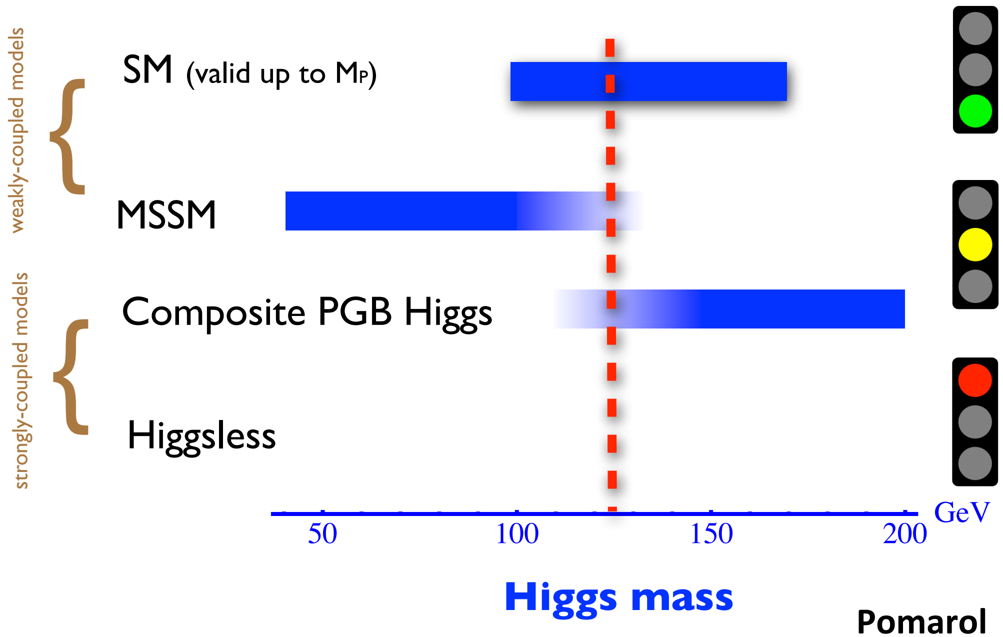
The 126 GeV Higgs Boson and SUSY

A blessing…

- Fundamental scalar -> SUSY
- Light and SM-like -> SUSY

Low energy SUSY prediction: Higgs mass up to ~135 GeV

Constrained SUSY prediction: SM-like Higgs with mass up to ~130 GeV



Pomarol

The 126 GeV Higgs Boson and SUSY

A blessing…

- Fundamental scalar -> SUSY
- Light and SM-like -> SUSY

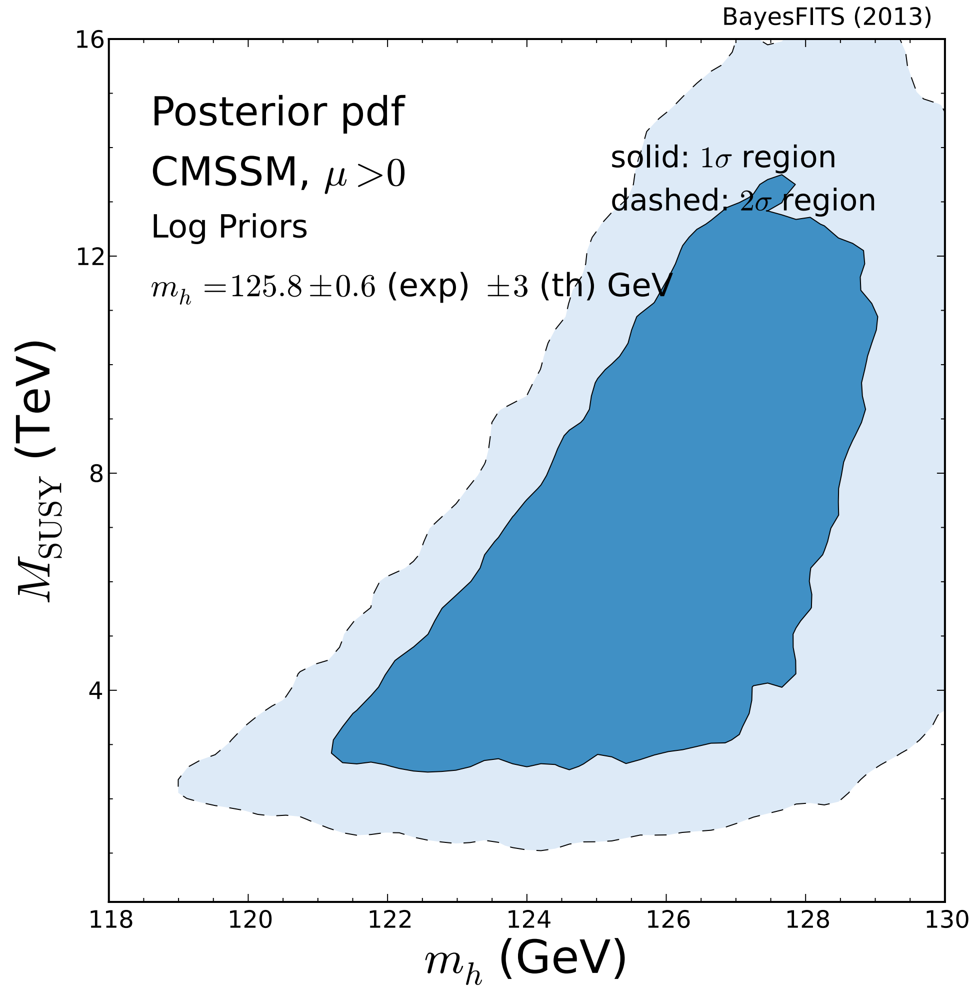
Low energy SUSY prediction: Higgs with mass up to ~135 GeV

Constrained SUSY prediction:
SM-like Higgs with mass up to ~130 GeV

The 126 GeV Higgs Boson and SUSY

A curse…

-> Multi-TeV scale of SUSY



Only m_h~126 GeV and CMS lower bounds on SUSY applied.

$$M_{\rm SUSY} \equiv \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$$

How to compare theory with experiment

- **Rigid step-function application of limits/allowed ranges (e.g. DM relic abundance, etc)** — **Mahmoudi et al, Hewett et al, …**
- **Frequentist (chi^2-based)** — **MasterCode, Fittino, …**
- **Bayesian** — **BayesFITS, Allanach, SuperBayes, Balazs, Kraml…**

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"

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

Both F and B are based on the likelihood function.

The Likelihood function

Central object: Likelihood function

- **Positive measurements:**

Take a single observable $\xi(m)$ that has been measured

(e.g., M_W)

- c – central value, σ – standard exptal error
- define

$$\chi^2 = \frac{[\xi(m)-c]^2}{\sigma^2}$$

- assuming Gaussian distribution ($d \to (c,\sigma)$):

$$\mathcal{L} = p(\sigma, c|\xi(m)) = \frac{1}{\sqrt{2\pi}\sigma}\exp\left[-\frac{\chi^2}{2}\right]$$

- when include theoretical error estimate τ (assumed Gaussian):

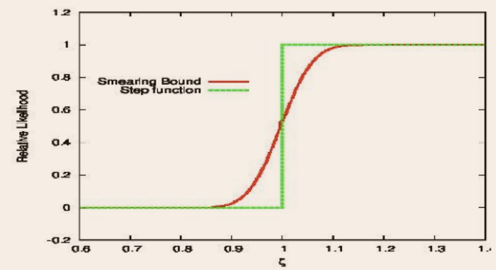
$$\sigma \to s = \sqrt{\sigma^2+\tau^2}$$

TH error "smears out" the EXPTAL range

- for several uncorrelated observables (assumed Gaussian):

$$\mathcal{L} = \exp\left[-\sum_i \frac{\chi_i^2}{2}\right]$$

- **Limits:**



- Smear out bounds.
- Add theory error.

- **LHC direct limits:**
  - Need careful treatment. Typically use Poisson.

Bayesian statistics

Bayes theorem: $$p(m|d) = \frac{p(d|m)\,\pi(m)}{p(d)}$$

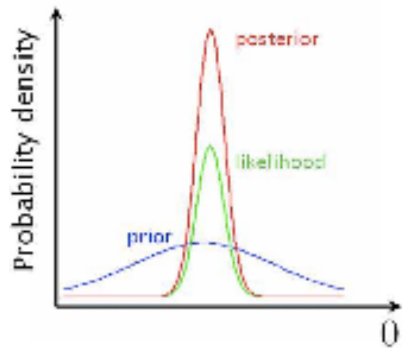
Prior $\pi(m)$ – what we know about the model m before seeing the data d

Likelihood $p(d|m)$ – the probability of obtaining data d if model m is true

Posterior $p(m|d)$ – the probability about m after seeing d.

Evidence $p(d)$ – normalization factor, important for model comparison

$$\text{Posterior} = \frac{\text{Prior} \times \text{Likelihood}}{\text{Evidence}}$$



If hypothesis is a function of parameters, then posterior becomes posterior probability function (pdf).

Posterior → credible regions at chosen CL

Minimum chi2 approach: find best-fit and draw confidence regions about it

Constrained Minimal Supersymmetric Standard Model (CMSSM)

G. L. Kane, C. F. Kolda, L. Roszkowski and J. D. Wells, Phys. Rev. D 49 (1994) 6173

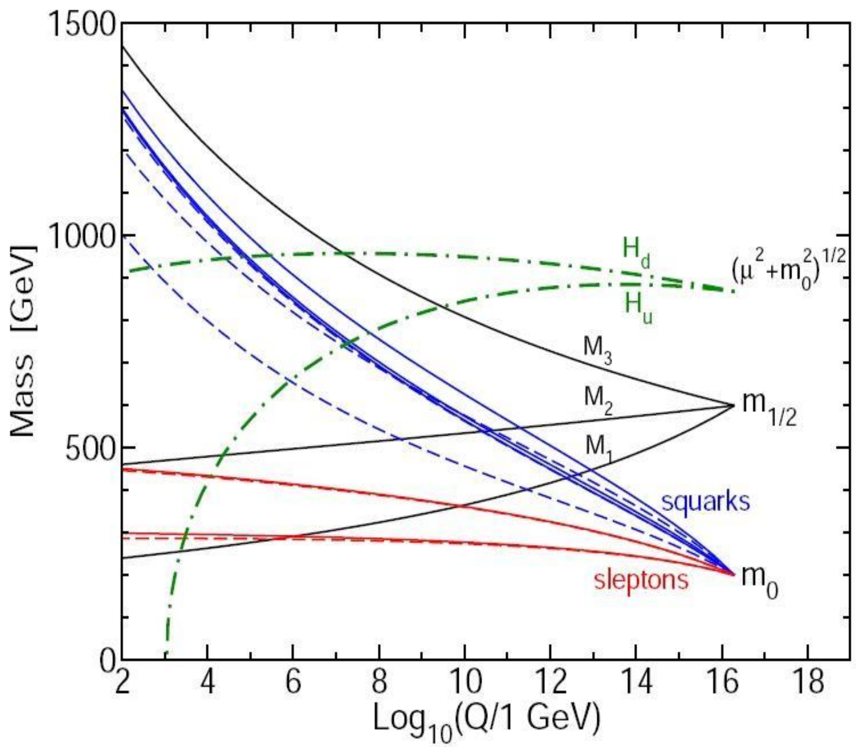


figure from hep-ph/9709356

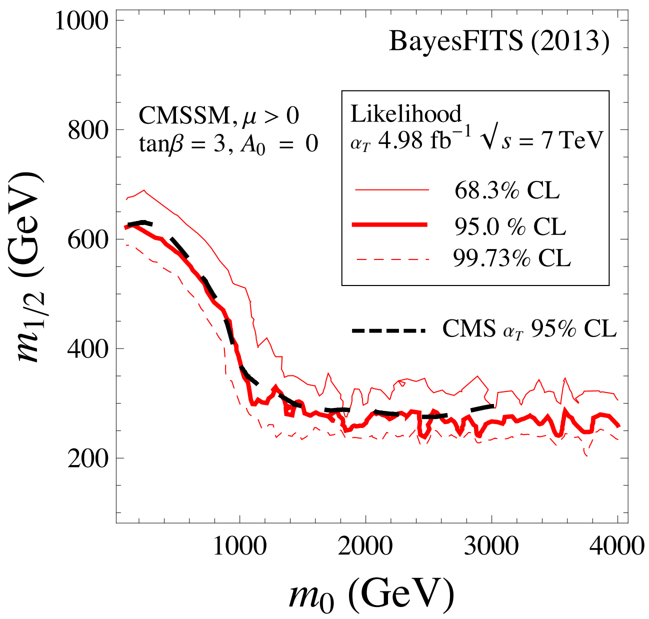
At $M_{\rm GUT} \simeq 2\times 10^{16}\,{\rm GeV}$:

- gauginos $M_1 = M_2 = m_{\tilde{g}} = m_{1/2}$
- scalars $m^2_{\tilde{q}_i} = m^2_{\tilde{l}_i} = m^2_{H_b} = m^2_{H_t} = m_0^2$
- 3–linear soft terms $A_b = A_t = A_0$
- radiative EWSB $\mu^2 = \frac{m^2_{H_b} - m^2_{H_t}\tan^2\beta}{\tan^2\beta - 1} - \frac{m_Z^2}{2}$
- five independent parameters: $m_{1/2},\ m_0,\ A_0,\ \tan\beta,\ {\rm sgn}(\mu)$
- well developed machinery to compute masses and couplings

Reproducing CMS limits on SUSY

We approximate CMS limits by deriving likelihood maps

First, validate our method:

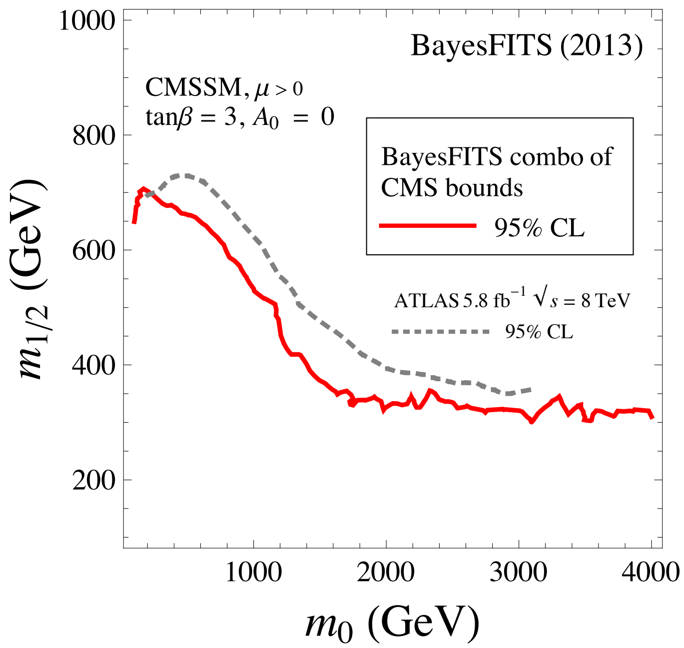


Excellent agreement

Next, derive combined CMS limit based on datasets:

α_T 11.7/fb, $\sqrt{s} = 8$ TeV

Razor 4.4/fb, $\sqrt{s} = 7$ TeV [1302.5956](1302.5956)



Applies to both signs of mu
And to similar models: NUHM, CNMSSM,…

Below will use combined CMS limit via likelihood function

Specialty of BayesFITS

CMSSM: numerical scans

- **Perform random scan over 4 CMSSM +4 SM (nuisance) parameters simultaneously**

- Very wide ranges: 1302.5956

$$100\,\mathrm{GeV} \le m_0 \le 20\,\mathrm{TeV}$$
$$100\,\mathrm{GeV} \le m_{1/2} \le 10\,\mathrm{TeV}$$
$$-20\,\mathrm{TeV} \le A_0 \le 20\,\mathrm{TeV}$$
$$3 \le \tan\beta \le 62$$

- Use Nested Sampling algorithm to evaluate posterior
- Use 4 000 live points

Nuisance	Description	Central value $\pm$ std. dev.	Prior Distribution
M_t	Top quark pole mass	$173.5 \pm 1.0\,\mathrm{GeV}$	Gaussian
$m_b(m_b)_{\mathrm{SM}}^{\overline{MS}}$	Bottom quark mass	$4.18 \pm 0.03\,\mathrm{GeV}$	Gaussian
$\alpha_s(M_Z)^{\overline{MS}}$	Strong coupling	0.1184 ± 0.0007	Gaussian
$1/\alpha_{\mathrm{em}}(M_Z)^{\overline{MS}}$	Inverse of em coupling	127.916 ± 0.015	Gaussian

Use Bayesian approach (posterior)

Hide and seek with SUSY

The experimental measurements that we apply to constrain the CMSSM's parameters. Masses are in GeV.

Measurement	Mean or Range	Error: (Exp., Th.)	Distribution
Combination of:			
CMS razor 4.4/fb , $\sqrt{s} = 7\,\text{TeV}$	See text	See text	Poisson
CMS α_T 11.7/fb , $\sqrt{s} = 8\,\text{TeV}$	See text	See text	Poisson
m_h by CMS	$125.8\,\text{GeV}$	$0.6\,\text{GeV}, 3\,\text{GeV}$	Gaussian
$\Omega_\chi h^2$	0.1120	0.0056, 10%	Gaussian
$\delta\,(g-2)_\mu^{\text{SUSY}} \times 10^{10}$	28.7	8.0, 1.0	Gaussian
$\text{BR}\,(\overline{B} \to X_s\gamma) \times 10^4$	3.43	0.22, 0.21	Gaussian
$\text{BR}\,(B_u \to \tau\nu) \times 10^4$	1.66	0.33, 0.38	Gaussian
ΔM_{B_s}	$17.719\,\text{ps}^{-1}$	$0.043\,\text{ps}^{-1},\ 2.400\,\text{ps}^{-1}$	Gaussian
$\sin^2\theta_{\text{eff}}$	0.23116	0.00012, 0.00015	Gaussian
M_W	80.385	0.015, 0.015	Gaussian
$\text{BR}\,(B_s \to \mu^+\mu^-)_{\text{current}} \times 10^9$	3.2	$+1.5 - 1.2$, 10% (0.32)	Gaussian
$\text{BR}\,(B_s \to \mu^+\mu^-)_{\text{proj}} \times 10^9$	3.5 (3.2*)	0.18 (0.16*), 5% [0.18 (0.16*)]	Gaussian

SM value: $\simeq 3.5 \times 10^{-9}$

10 dof

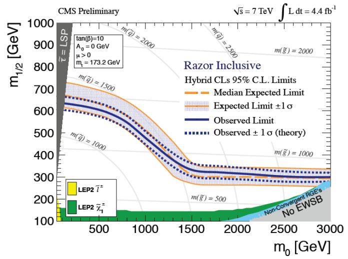
SUSY - most important constraints:

- **Higgs mass**

CMS: $m_h \sim 125.8$ GeV (in ZZ); $m_h = 124.9.$ GeV (in γγ)

ATLAS: $m_h = 124.3$ GeV (in ZZ); $m_h = 126.8$ GeV (in γγ)

- **Direct search limits**



Lower limit…

- **Dark matter density**

Positive measurement, **inconsistent with SM**

- **B_s -> mu mu**

$$\mathbf{BR}(\overline{B}_s \to \mu^+\mu^-) = \left(3.2^{+1.5}_{-1.2}\right) \times 10^{-9}$$

LHCb (Nov 2012)

- **Other flavor (b to s gamma, etc)**
- **EW observables (M_W,…)**
- **(g-2)_muon**

Bayes FITS

~126 GeV Higgs in SUSY

- **In SUSY m_h is a calculated quantity.**
- **1-loop corr: positive, up to ~45 GeV**

$$\Delta m_h^2 = \frac{3m_t^4}{4\pi^2 v^2}\left[\ln\left(\frac{M_{\rm SUSY}^2}{m_t^2}\right) + \frac{X_t^2}{M_{\rm SUSY}^2}\left(1 - \frac{X_t^2}{12M_{\rm SUSY}^2}\right)\right]$$

- **2-loop corr: negative, ~3 GeV**

two most complete calculations differ by a 2-5 GeV (DR-bar (Slavich,…) used in SoftSusy, Spheno, Suspect, and on-shell (Hollik,…) in FeynHiggs

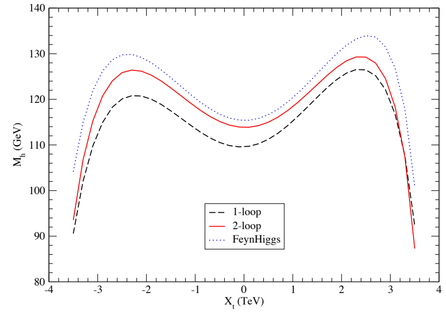
Substantial theory error!

Not yet implemented in codes

- **(3-loop corr: positive, <~2-3 GeV)**

P. Kant
J. Feng, et al

Djouadi, arXiv:hep-ph/0503173



$$M_{\rm SUSY} \equiv \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$$

$$X_t = A_t - \mu \cot\beta$$

Two ways to obtain m_h~126 GeV:
1. **increase M_SUSY -> heavy superparners!**

or

2. **take large |X_t|~|A_t| -> stop_1 at ~1TeV**

Applies to SUSY generally, not just constrained models.

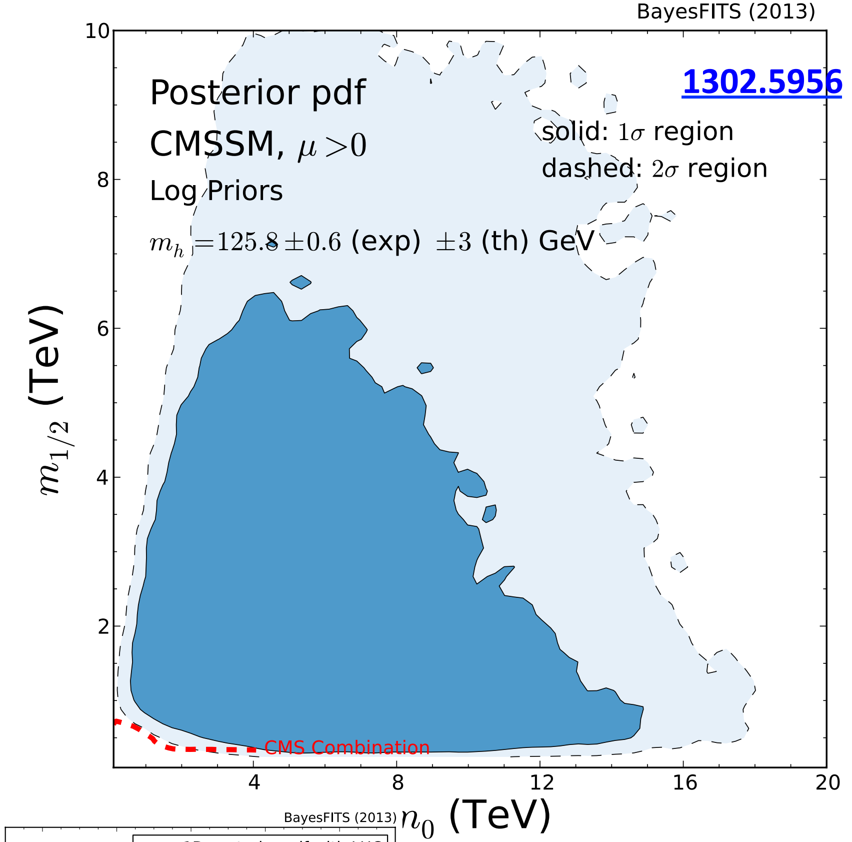
~126 GeV Higgs in the CMSSM

- Include <u>only</u> m_h~126 GeV
  and lower limits from direct
  SUSY searches

$$\mathcal{L} \sim e^{\frac{(m_h - 125.8\,\mathrm{GeV})^2}{\sigma^2+\tau^2}}$$

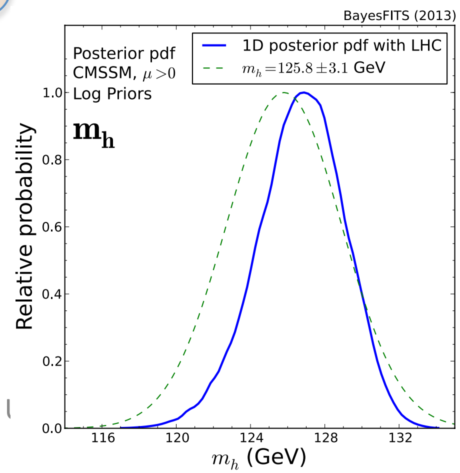
$$\sigma = 0.6\ \mathrm{GeV}, \tau = 2\ \mathrm{GeV}$$

We use DR-bar approach (SoftSusy). It gives larger m_h.



~126 GeV Higgs mass implies multi-TeV scale for SUSY

Consistent with:
- SUSY direct search lower limits at LHC
- constraints from flavor



A weak upper bound on M_SUSY

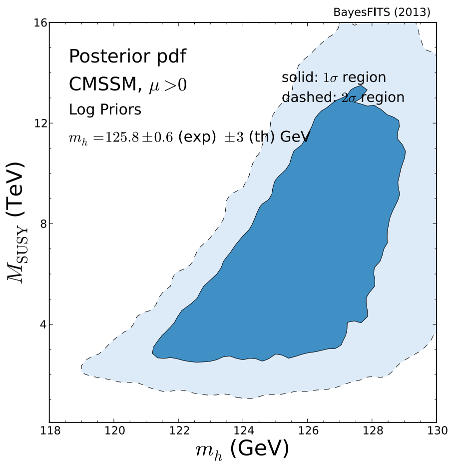
…except at very small tanb->1 where it goes away

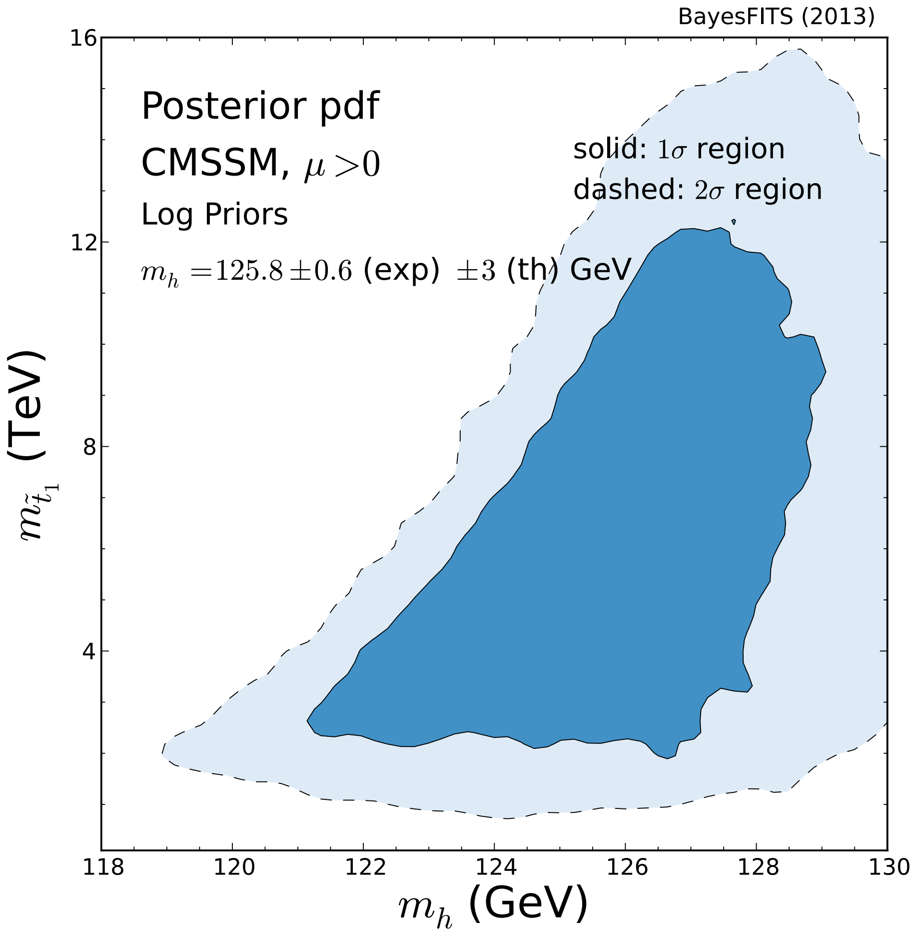
A curse…

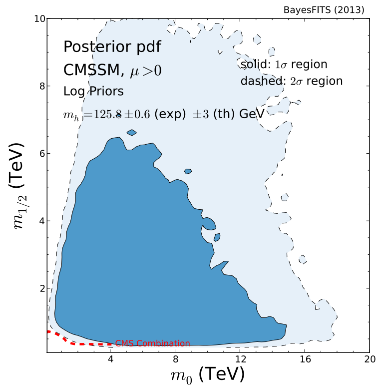
126 GeV - worst possible value (G. Giudice)

~126 GeV Higgs in the CMSSM

Include only m_h~126 GeV and lower limits from direct SUSY searches



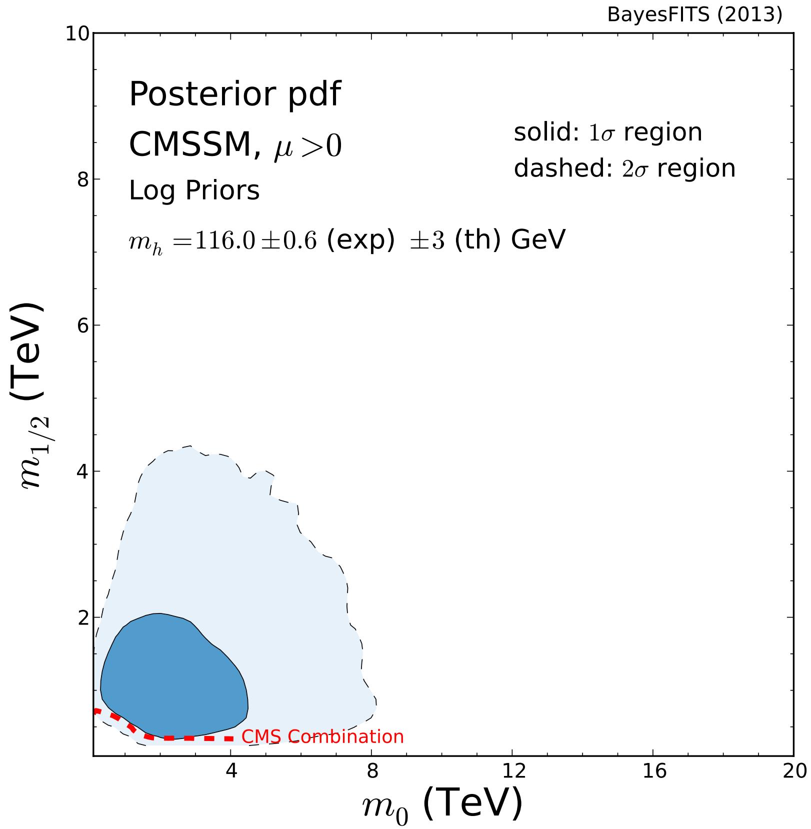


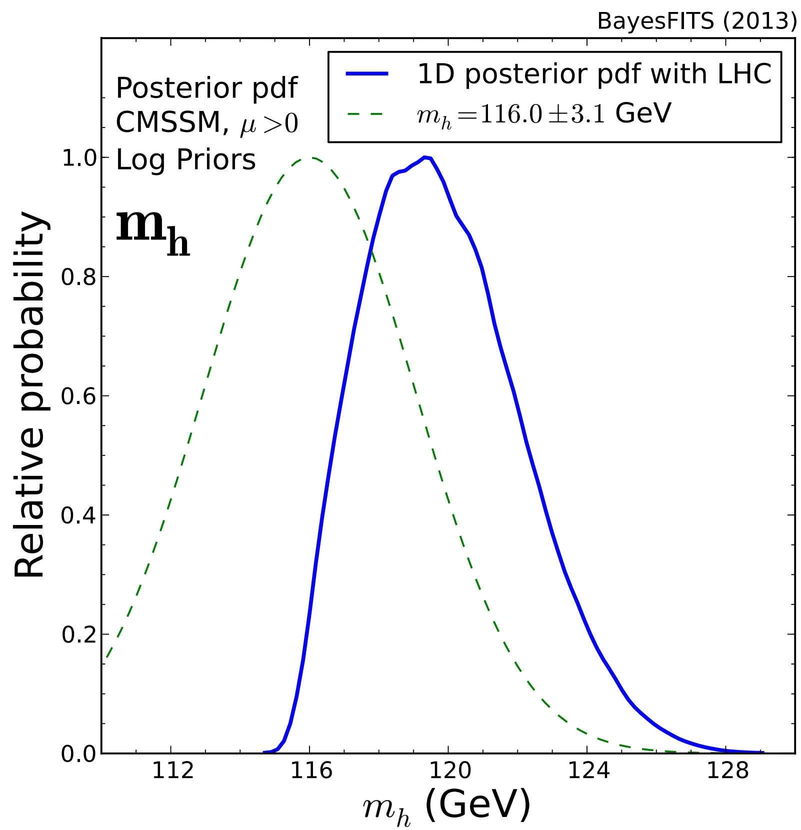


A weak upper bound as well.

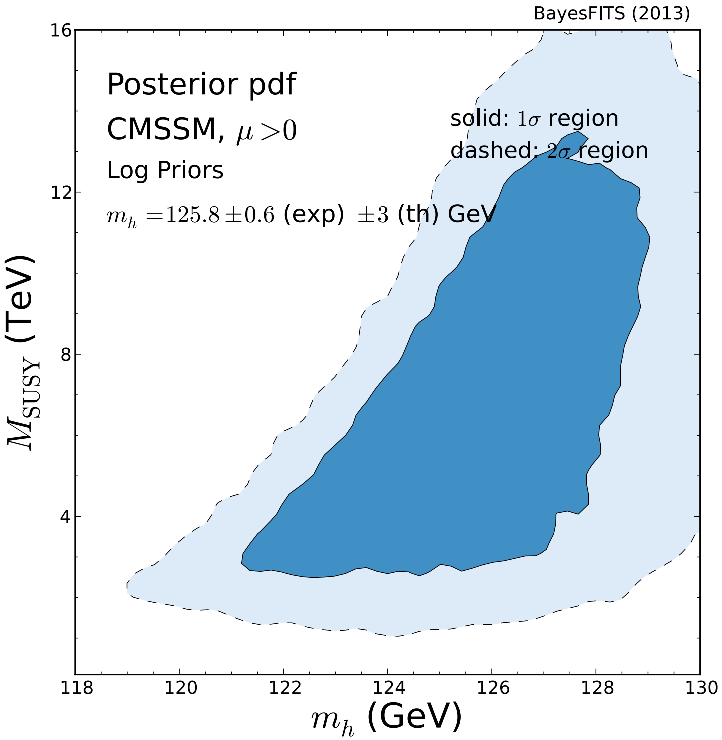
~126 GeV Higgs mass implies multi-TeV SUSY masses

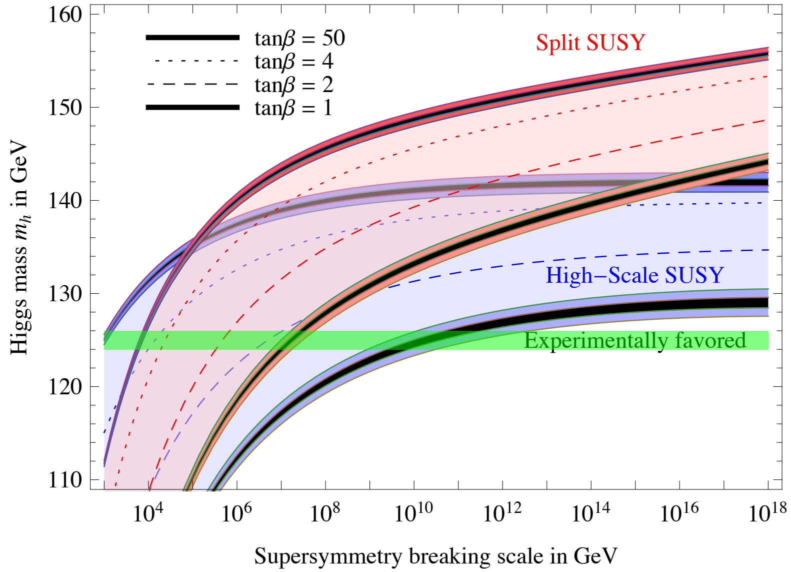
If m_h were, e.g., 116 GeV…





…significant tension with LHC bounds





Degrassi, et al., 1205.6497
(Abreu, …)

A weak upper bound on M_SUSY

Even weaker for small tanbeta

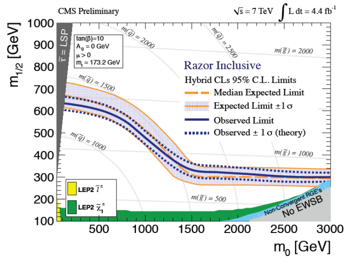
Generically ~126 GeV Higgs mass implies multi-TeV scale for SUSY

SUSY - most important constraints:

- **Higgs mass**

CMS: m_h ~ 125.8 GeV (in ZZ); m_h = 124.9. GeV (in $\gamma\gamma$)

ATLAS: m_h = 124.3 GeV (in ZZ); m_h = 126.8 GeV (in $\gamma\gamma$)



- **Direct search limits**

Lower limit…

- **Dark matter density**

Positive measurement, inconsistent with SM

- **B_s -> mu mu**

$$\mathrm{BR}(\overline{B}_s \to \mu^+\mu^-) = \left(3.2^{+1.5}_{-1.2}\right) \times 10^{-9}$$

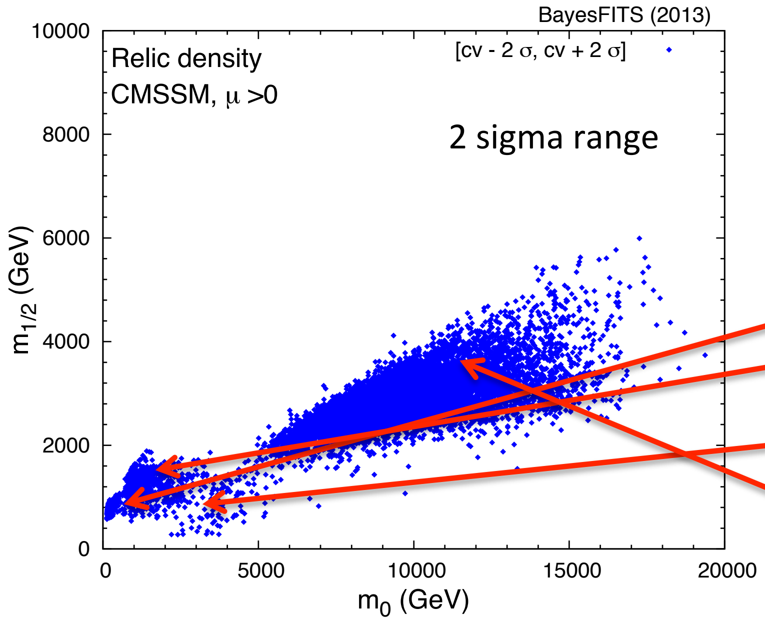
LHCb (Nov 2012)

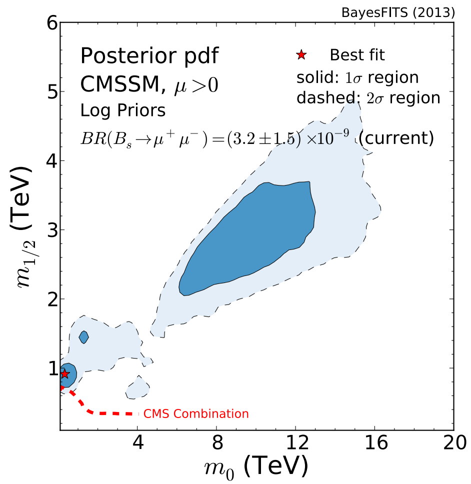
- **Other flavor (b to s gamma, etc)**
- **EW observables (M_W,…)**
- **(g-2)_muon**

Dark matter density

- **Unified SUSY: neutralino relic density is typically 1-2 orders of magnitude too large**

Measurement	Mean or Range	Error: (Exp., Th.)	Distribution
$\Omega_\chi h^2$	0.1120	0.0056, 10%	Gaussian





1302.5956

Remaining mechanisms of reducing it to correct range:

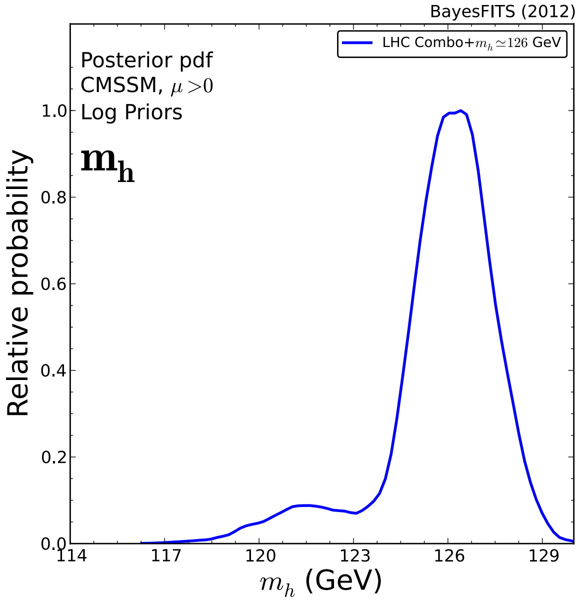
- ✧**neutralino-stau coannhilation**
- ✧**pseudoscalar Higgs A resonance** $\Omega h^2 \propto m_A^4/\tan^2\beta$
- ✧**focus point/hyperbolic branch region**
- ✧**~1 TeV higgsino LSP at large MSUSY**
- ✧**and (very rare) LSP-stop coannihilation**

Scan with all other relevant constraints imposed

CMSSM: these are the only DM-favored regions

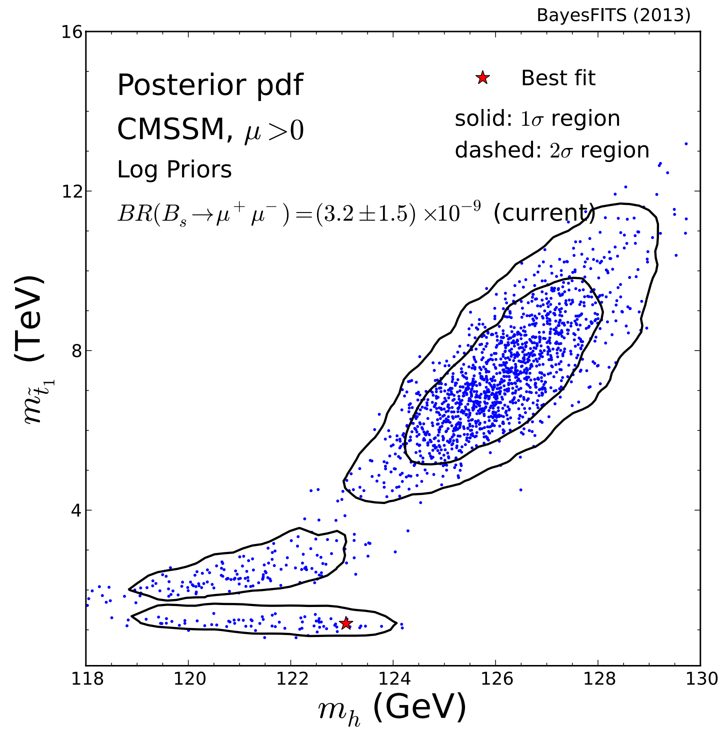
~126 GeV Higgs vs stop mass

1302.5956



...with all relevant constraints imposed

Stop_1 mass at or above 1 TeV



Best fit to ~126 GeV Higgs for M_SUSY~1 TeV or >> 1 TeV

$$\text{best-fit point } \chi^2_{\min}/\text{dof} = 18.26/10$$

$$[\chi^2_{\min}/\text{dof} \simeq 4/9 \text{ when drop } (g-2)_\mu]$$

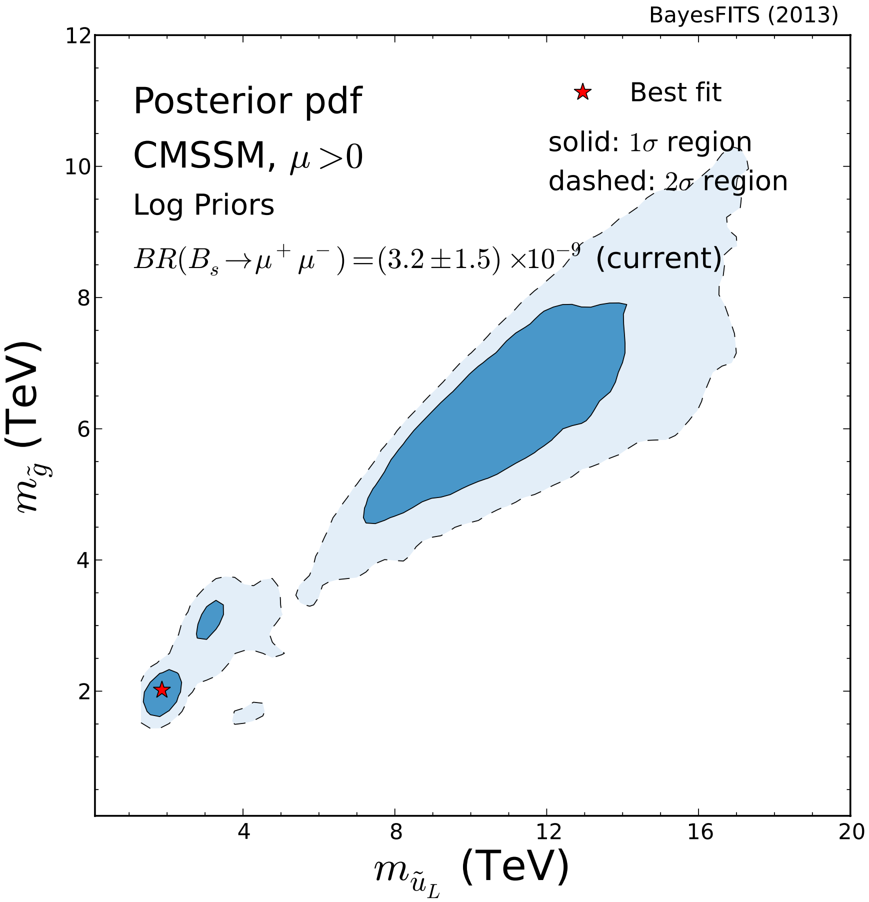
Dark matter density selects specific regions

- CMSSM: DM regions (almost) disconnected
- other models: they overlap

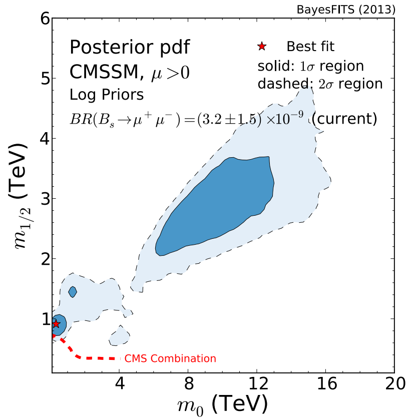
Can such multi-TeV ranges of SUSY parameters be experimentally tested?

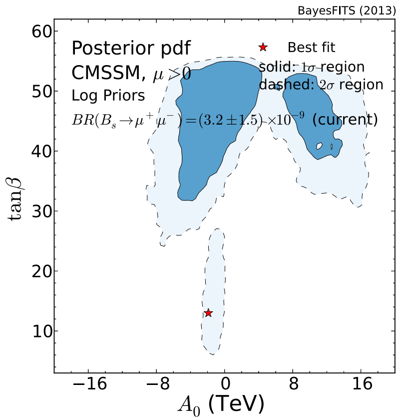
Are we done with the LHC?

gluino mass



Squark mass (1st or 2nd gen)



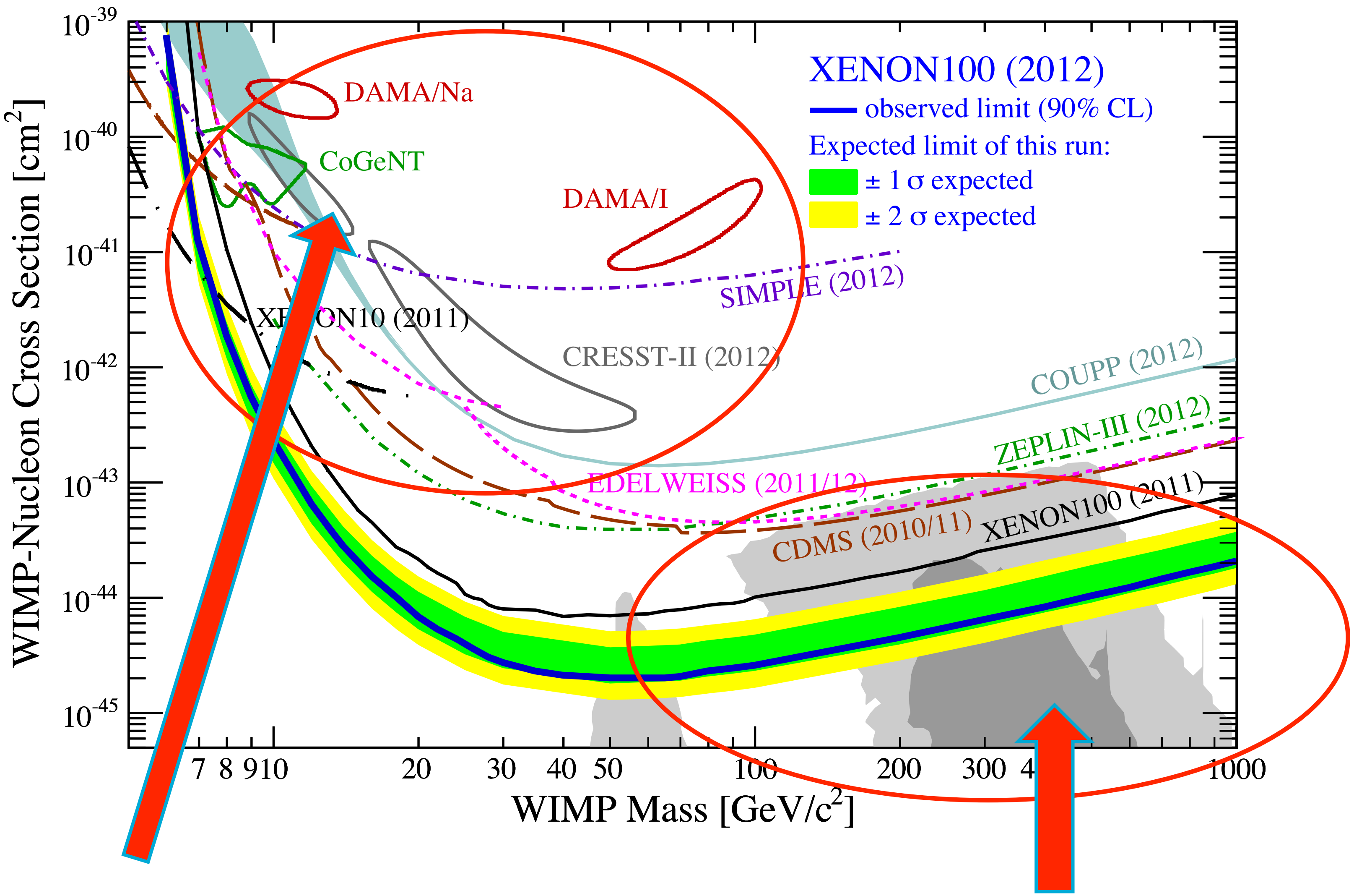


LHC reach:
Gluino: ~2.7 GeV
Squarks: ~3 TeV

LHC - …signal ``not guaranteed''


There is more out there than meets the eye
al. et Frenk

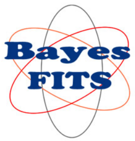
Direct Detection AD 2011 - Before LHC



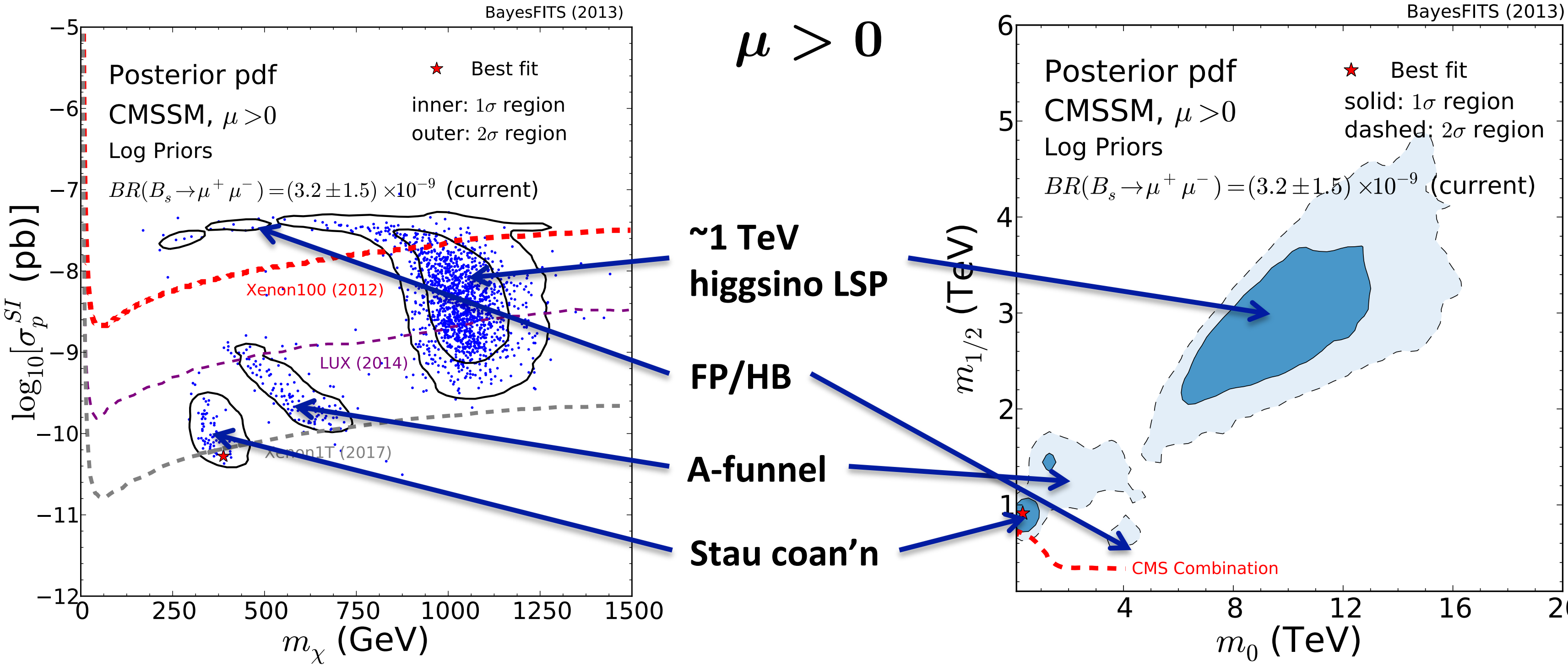
Confusion region

motivated by theory (SUSY)

MasterCode, BayesFITS



CMSSM and 1-tonne DM detectors



1-tonne DM detectors to cover most of CMSSM predictions

…over ALL multi-TeV ranges of mass parameters

(Except for some cases at mu<0)

Generic prediction of multi-TeV SUSY: ~1TeV LSP (higgsino)

LUX (2014) to improve sensitivity by ~1 decade

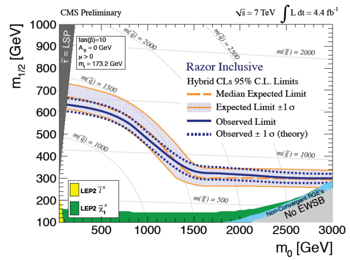
SUSY - most important constraints:

- **Higgs mass**

CMS: $m_h \sim 125.8$ GeV (in ZZ); $m_h = 124.9.$ GeV (in $\gamma\gamma$)

ATLAS: $m_h = 124.3$ GeV (in ZZ); $m_h = 126.8$ GeV (in $\gamma\gamma$)

- **Direct search limits**



Lower limit…

- **Dark matter density**

Positive measurement, **inconsistent with SM**

- **B_s -> mu mu**

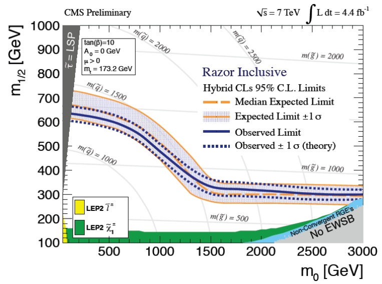
$$\mathrm{BR}(\overline{B}_s \to \mu^+\mu^-) = \left(3.2^{+1.5}_{-1.2}\right) \times 10^{-9}$$

LHCb (Nov 2012)

- **Other flavor (b to s gamma, etc)**
- **EW observables (M_W,…)**
- **(g-2)_muon**

SUSY: most important constraints:

- **Dark matter density** — Positive measurement, inconsistent with SM



- **Direct search limits**

Lower limit…

- **The Higgs mass**

CMS: $m_h \sim 125.8$ GeV (in ZZ); $m_h = 124.9.$ GeV (in $\gamma\gamma$)

ATLAS: $m_h = 124.3$ GeV (in ZZ); $m_h = 126.8$ GeV (in $\gamma\gamma$)

- **B_s -> mu mu**

$$\mathrm{BR}(\overline{B}_s \to \mu^+\mu^-) = \left(3.2^{+1.5}_{-1.2}\right) \times 10^{-9}$$

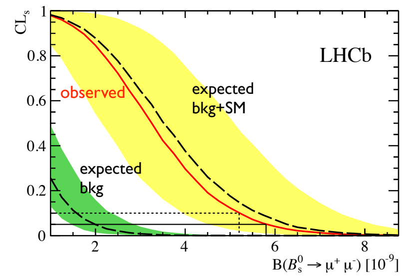
LHCb (Nov 2012)

- **Other flavor (b to s gamma, etc)**
- **M_W, EW,…**
- **(g-2)_muon**

BR(Bs->mu mu)

$$\mathrm{BR}(\overline{B}_s \to \mu^+\mu^-) = \left(3.2^{+1.5}_{-1.2}\right) \times 10^{-9}$$

M. Palutan (LHCb), 13 Nov 2012



$1.1\times 10^{-9} < \mathcal{B}(B^0_s \to \mu^+\mu^-) < 6.4\times10^{-9}$ at 95% CL

Note this gives weaker upper bound than before.

LHC combination (June 2012): $\mathcal{B}(B^0_s\to\mu^+\mu^-)<4.2\times10^{-9}$ at 95% CL

LHCb-CONF-2012-017
CMS-PAS-BPH-12-009
ATLAS-CONF-2012-061

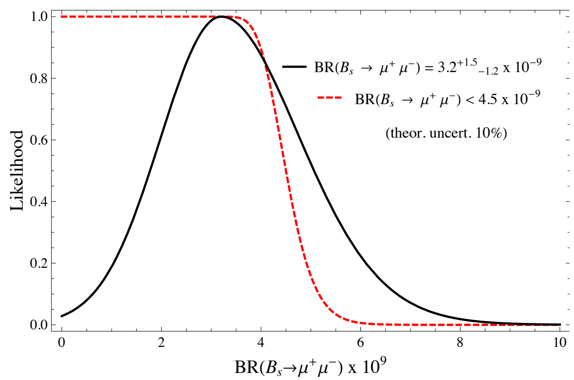
$$\mathcal{B}(B^0_s \to \mu^+\mu^-)^{\langle t \rangle} = \frac{1}{1-y_s} \cdot \mathcal{B}(B^0_s \to \mu^+\mu^-)^{t=0} = (3.54 \pm 0.30)\cdot 10^{-9}$$

SM value

De Bruyn et al., PRL 109, 041801 (2012) uses LHCb-CONF-2012-002

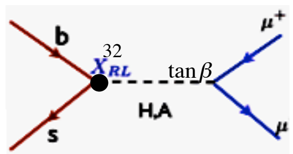
We approximate the signal with a Gaussian

Note the Gaussian Like allows larger BR than 4.2 bound before.



– sensitive probe of new physics

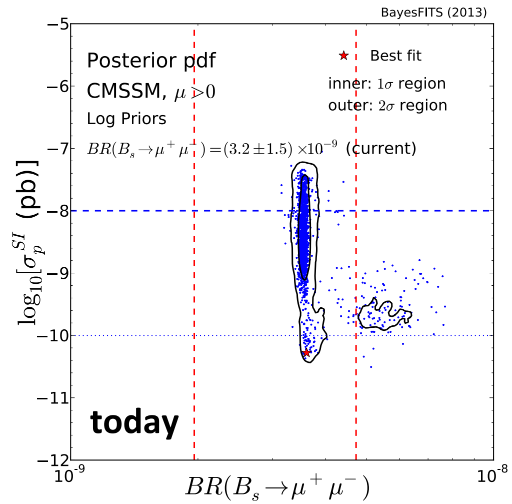
$$\mathrm{BR}(\overline{B}_s \to \mu^+\mu^-) \propto \tan^6\beta/m_A^4$$

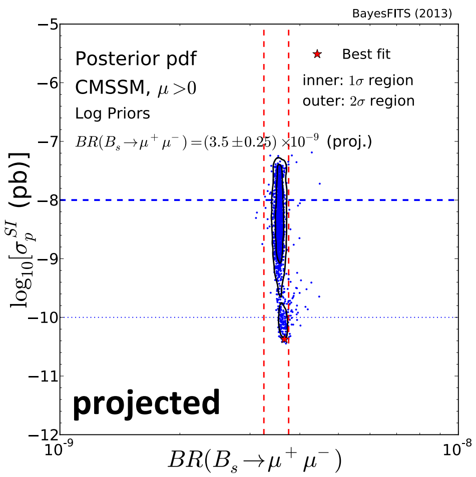


LHCb result agrees with SM value => limits on SUSY

Effect of precise BR($\overline{B}_s \to \mu^+\mu^-$)

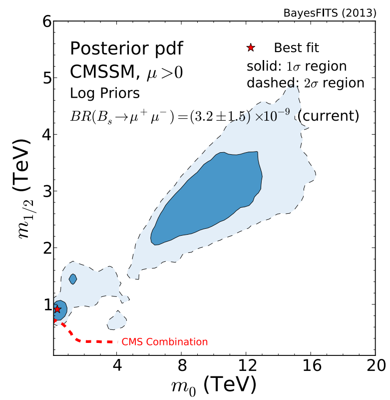
mu>0

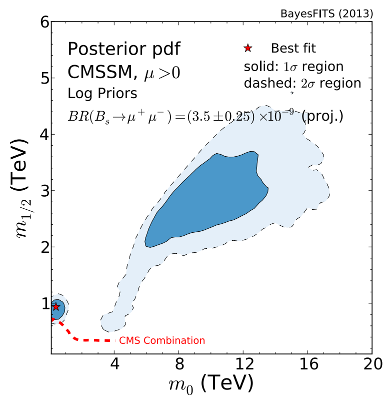




If BR($\overline{B}_s \to \mu^+\mu^-$) $\simeq$ SM value with 5-10% precision (both TH and EXPT)

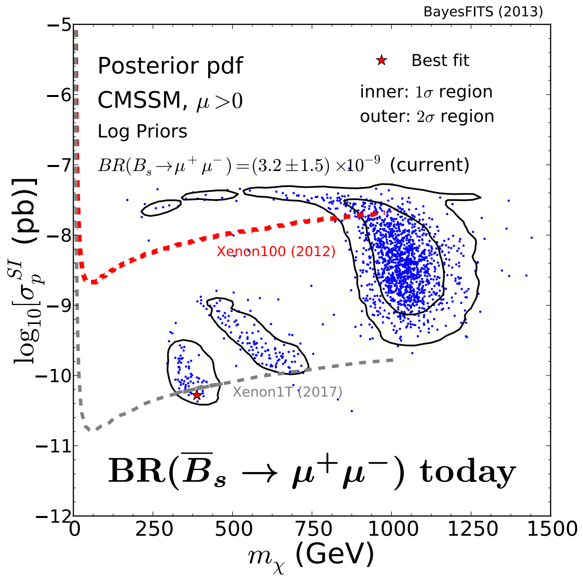
$\Rightarrow$ A funnel region gone

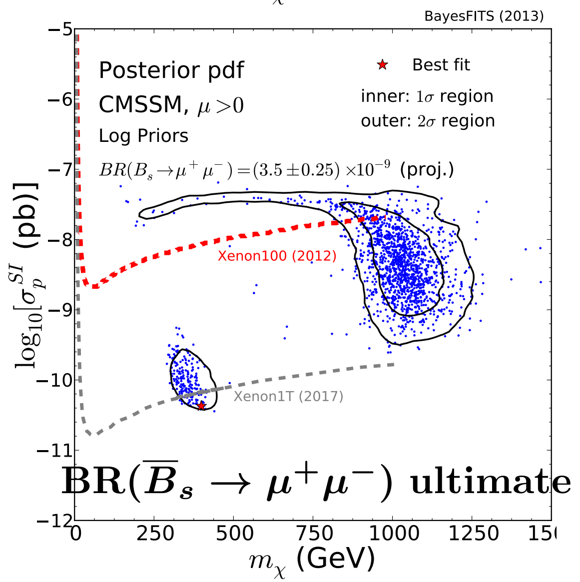




Effect of precise $\mathrm{BR}(\overline{B}_s \to \mu^+\mu^-)$

mu>0





If $\mathrm{BR}(\overline{B}_s \to \mu^+\mu^-) \simeq$ SM value with 5-10% precision $\Rightarrow$ A funnel region gone

Ways to rule out the CMSSM:
- **No DM signal in 1-tonne detectors**
- **DM signal at ~500 to 750 GeV**

SC: for $\mu < 0$ σ_p^{SI} lower (cancellations)

NUHM, CNMSSM: similar ranges of sigma_p but DM-favored regions overlap

Constrained SUSY is alive and well…

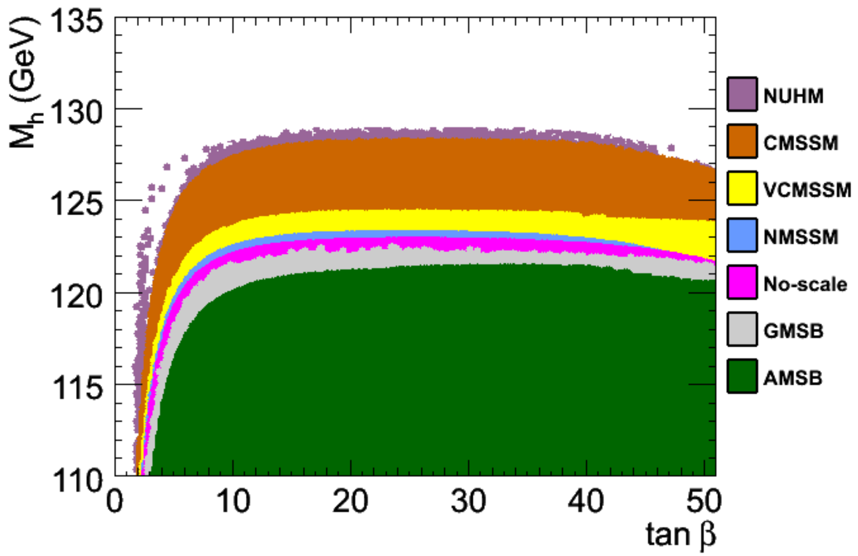
- **Even the simplest unified SUSY model (CMSSM) is consistent with all data (Higgs mass, DM relic density, direct limits, flavor-violating processes, …)**

…except for g-2, R(gamma gamma)

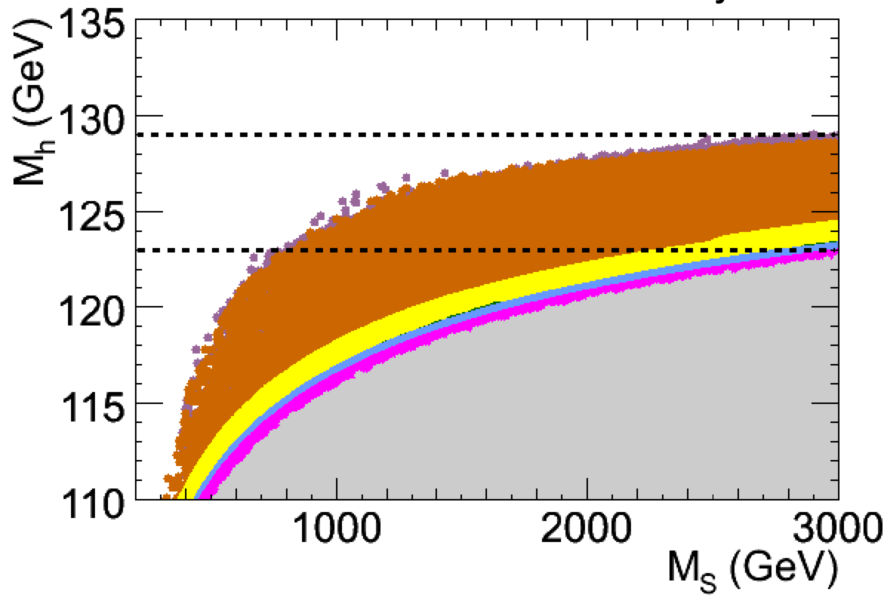
- **M_SUSY >~ (or even >>) 1 TeV favored by ~126 GeV Higgs**
- **In less unified models somewhat lower SUSY masses are allowed (but not by much)**

…except for very fine tuned corners

CMSSM and beyond



Djouadi



- **Generally: ~126 GeV Higgs: need ~>1TeV, typically multi-TeV M_SUSY scale**
- **Warning: different models scanned with different ranges, precision, completeness, etc**

CNMSSM…

Constrained Non-Minimal SSM

- The MSSM suffers from the mu-problem: $\mu \sim \mathcal{O}(M_{\rm SUSY})$
- The NMSSM extends the MSSM by addition of a gauge singlet superfield *S*

$$W = \lambda S H_u H_d + \frac{\kappa}{3} S^3 + (\text{Yukawa couplings})$$

S gets a vev $s = \langle S \rangle$ ==> Superpotential develops an effective term $\mu_{\rm eff} = \lambda s$

- Extra terms in the soft SUSY-breaking Lagrangian for the Higgs Sector

$$V_{\rm soft} = m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 + m_S^2 |S|^2 + \left(\lambda A_\lambda S H_u H_d + \frac{1}{3}\kappa A_\kappa S^3 + \text{h. c.}\right)$$

Higgs and neutralino sectors extended wrt MSSM: → +1 CP-even scalar
+1 CP-odd pseudoscalar
+1 neutralino

Leads to interesting phenomenology ↓

Richer Higgs phenomenology than MSSM:

→ $m_{h_1} \simeq 125$ GeV, h_2 *undetected*
→ $m_{h_2} \simeq 125$ GeV, h_1 *undetected*
→ $m_{h_1} \simeq m_{h_2} \simeq 125$ GeV
→ $m_{h_1} \simeq m_{a_1} \simeq 125$ GeV ← **particularly interesting case**

Global Bayesian analysis of the CNMSSM

arXiv:1211.1693

CNMSSM parameters:

$$m_0, m_{1/2}, A_0, \tan\beta, \lambda, \mathrm{sgn}(\mu_{\mathrm{eff}})$$

Measurement	Mean or range	Error (Exp., Th.)	Distribution
CMS razor 4.4/fb	Likelihood map		Poisson
$m_{h_{\mathrm{sig}}}$ (GeV)	125.8	0.6, 3	Gaussian
$R_{h_{\mathrm{sig}}}(\gamma\gamma)$	1.6	0.4, 15%	Gaussian
$R_{h_{\mathrm{sig}}}(ZZ)$	0.80	$+0.35-0.28$, 15%	Gaussian
$m_{h_{\mathrm{hid}}}$ (GeV)	< 122.7, > 128.9	0, 3	Error Fn
$R_{h_{\mathrm{hid}}}(X)$	$\mu_{95}(X)$ from CMS	0, 15%	Error Fn
$\Omega_\chi h^2$	0.1120	0.0056, 10%	Gaussian
$\delta(g-2)_\mu^{\mathrm{SUSY}} \times 10^{10}$	28.7	8.0, 1.0	Gaussian
$\mathrm{BR}(\overline{\mathrm{B}} \to \mathrm{X_s}\gamma) \times 10^4$	3.43	0.22, 0.21	Gaussian
$\mathrm{BR}(\mathrm{B_u} \to \tau\nu) \times 10^4$	1.66	0.66, 0.38	Gaussian
ΔM_{B_s} (ps^{-1})	17.719	0.043, 2.400	Gaussian
$\mathrm{BR}(\mathrm{B_s} \to \mu^+\mu^-)$	3.2×10^{-9}	$+1.5-1.2$, 10%	Gaussian

CNMSSM parameter	Prior Range	Prior Distribution
m_0	100 - 4000 (GeV)	Log
$m_{1/2}$	100 - 2000 (GeV)	Log
A_0	-7000 - 7000 (GeV)	Linear
$\tan\beta$	3 - 62	Linear
λ	0.0001 - 0.7	Linear
Nuisance	Central value $\pm$ error	Prior Distribution
M_t	172.9 ± 1.1 (GeV)	Gaussian
$m_b(m_b)_{\mathrm{SM}}^{\overline{MS}}$	4.19 ± 0.12 (GeV)	Gaussian
$\alpha_s(M_Z)^{\overline{MS}}$	0.1184 ± 0.0007	Gaussian

We do not assume $m_S^2 = m_0^2$

<u>LHC constraints:</u>

- CMS Razor limit on (m_0,m_1/2)
- For a \`signal' Higgs: $\mathcal{L}_{\psi_i}(h_{\mathrm{sig}}) = \exp\left[(\psi_i(\mathrm{obs}) - \psi_i(h_{\mathrm{sig}}))^2/2(\tau_{\psi_i}^2 + \sigma_{\psi_i}^2)\right]$

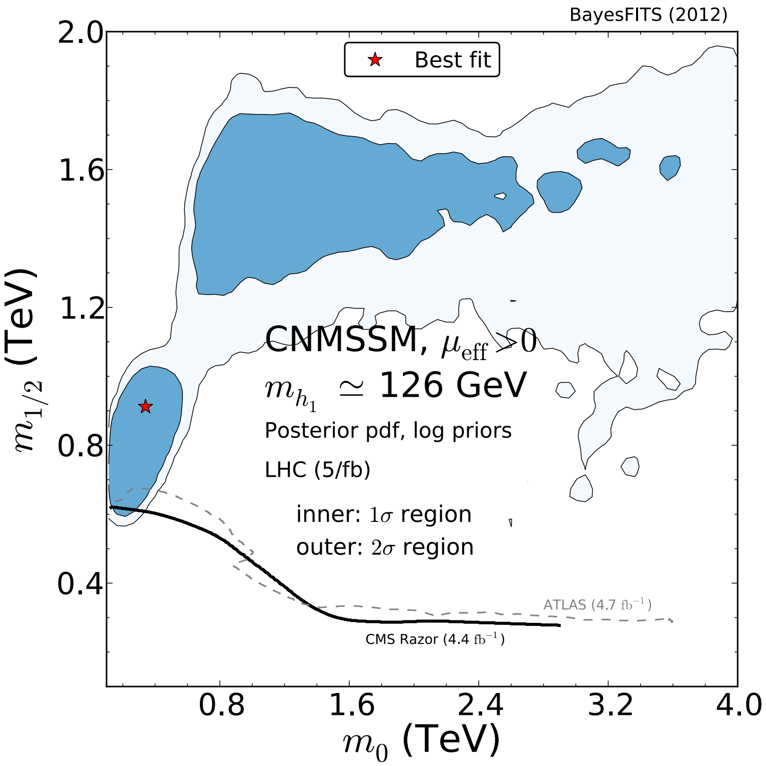
$$\psi_i = m(h_{\mathrm{sig}}),\ R_X(h_{\mathrm{sig}});\ R_X(h_{\mathrm{sig}}) = \frac{\sigma(pp\to h_{\mathrm{sig}})}{\sigma(pp\to h_{\mathrm{SM}})} \times \frac{BR(h_{\mathrm{sig}}\to X)}{BR(h_{\mathrm{SM}}\to X)};$$

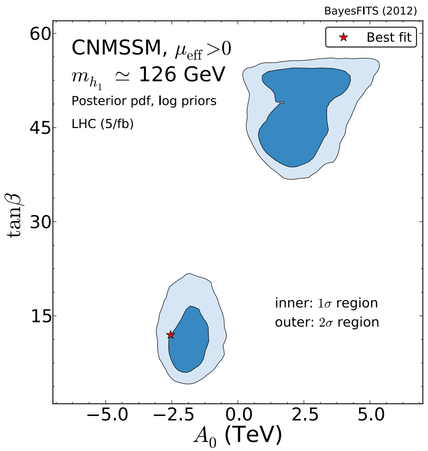
$$R_X(obs) \simeq \frac{\sigma_X}{\sigma_{SM}}\ (\mathrm{CMS})\ \text{for } X = \gamma\gamma,\ ZZ$$

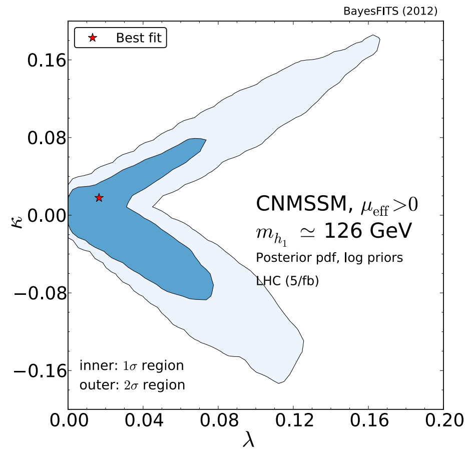
- For the unobserved Higgs: an exclusion likelihood for mass and R_X $X = \gamma\gamma, ZZ, \tau\tau, WW$

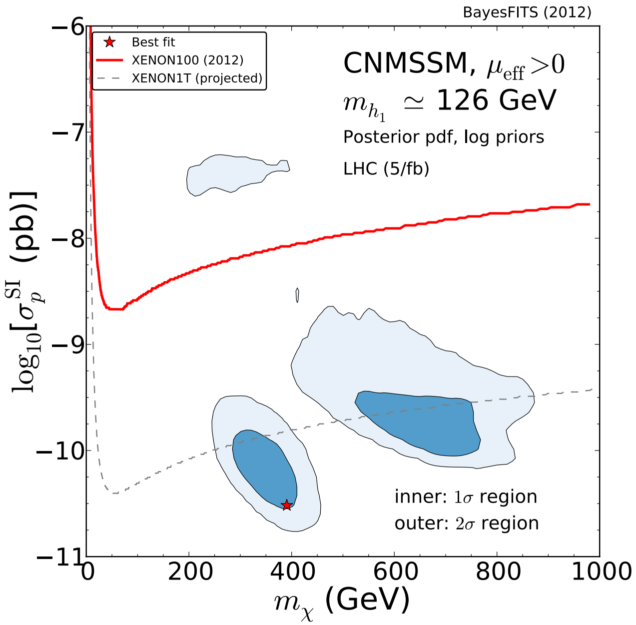
Constrained NMSSM

Case $m_{h_1} \simeq 126$ GeV







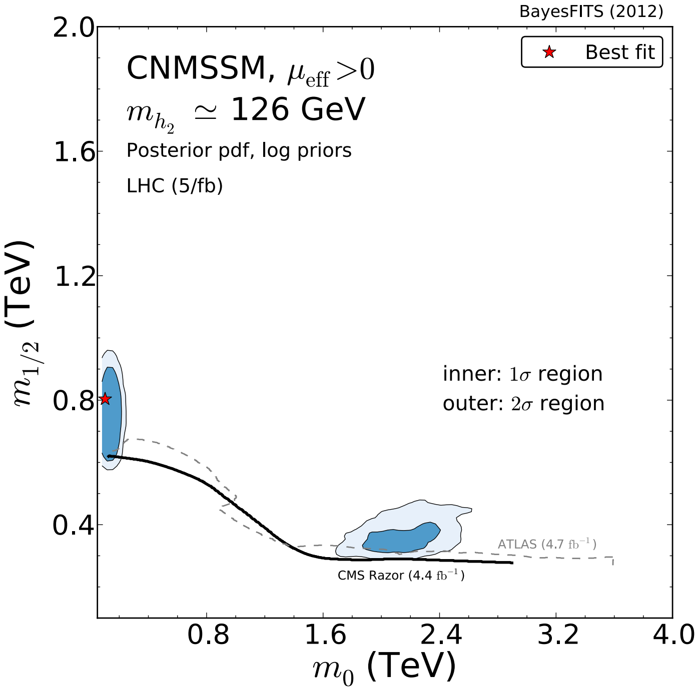


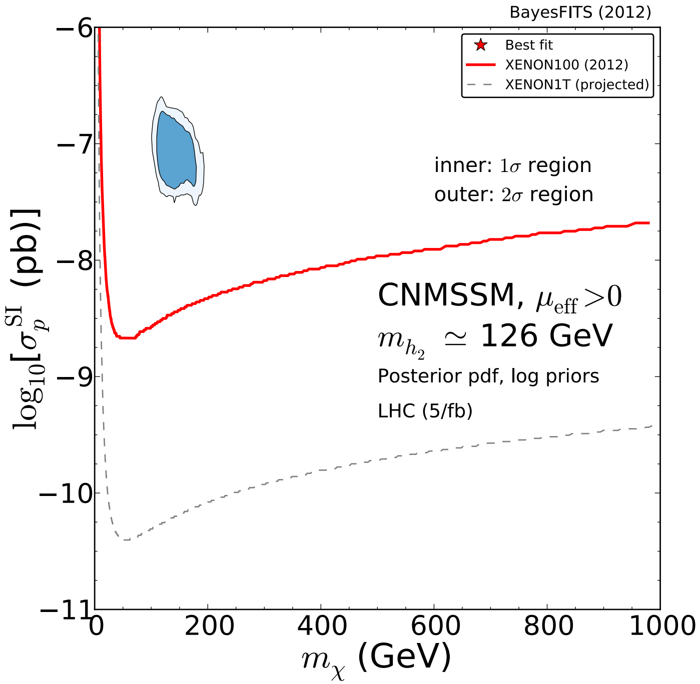
Global Bayesian analysis:
CNMSSM favors the CMSSM limit

arXiv:1211.1693

Constrained NMSSM

Case $m_{h_2} \simeq 126$ GeV





...excluded by Xenon100 limit on DM

arXiv:1211.1693

Constrained NMSSM

Case $m_{h_1} \simeq m_{a_1} \simeq 126\,\mathrm{GeV}$

arXiv:1305.0591

- requires relaxing strict CNMSSM conditions

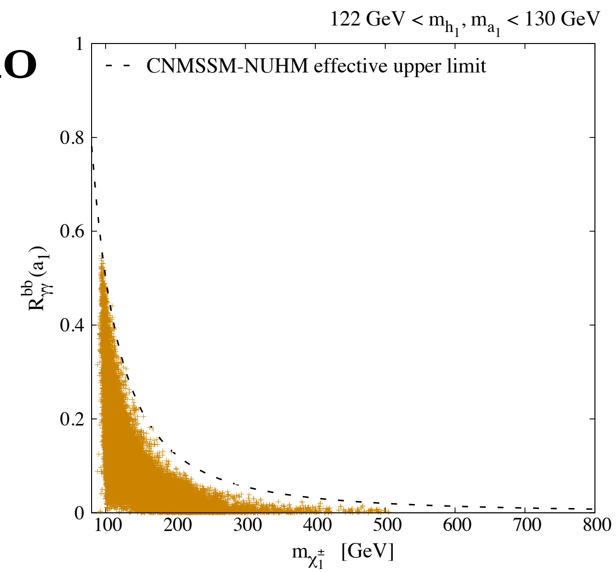
$m_{H_u}, m_{H_d}, m_S \neq m_0$ (CNMSSM-NUHM) $\qquad A_\lambda = A_\kappa \neq A_0$

Goal: boost $\gamma\gamma$ mode but keep ZZ/WW SM-like

h_1: SM-like (doublet-dominated)

a_1: singlet-dominated with enhanced $a_1 \to \gamma\gamma$

this requires light higgsino-like chargino



$$R^Y_{\gamma\gamma}(\mathrm{obs}) = R^Y_{\gamma\gamma}(h_1) + R^Y_{\gamma\gamma}(a_1) \simeq 1 + R^Y_{\gamma\gamma}(a_1)$$

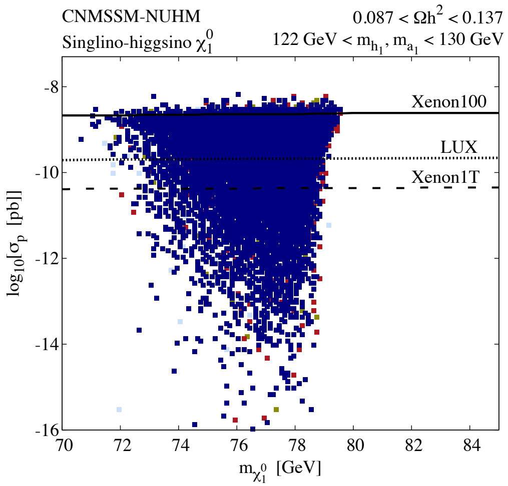
$$R^Y_{WW/ZZ}(\mathrm{obs}) = R^Y_{WW/ZZ}(h_1) \simeq 1$$

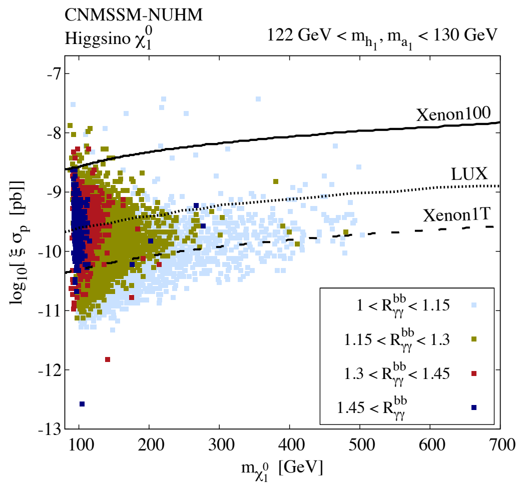
Three solutions:

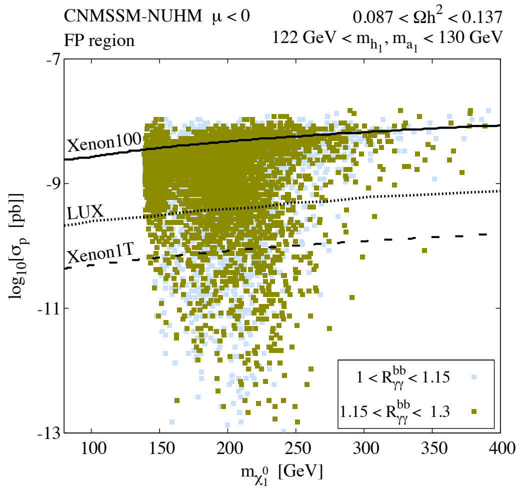
- **LSP singlino-higgsino like**
- **LSP higgsino like**
- **LSP bino-higgsino like (Focus Point, FP)**

Three solutions:

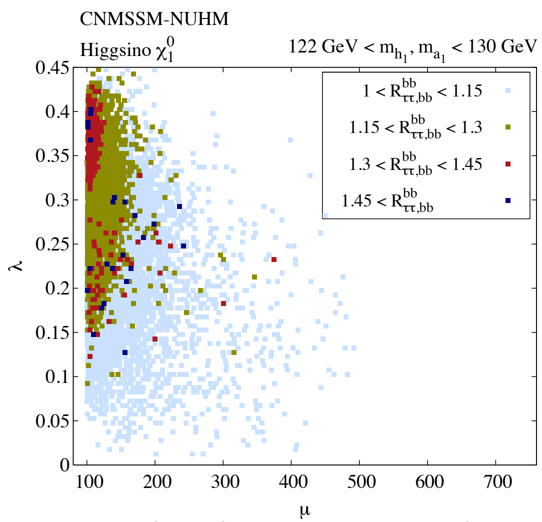
- **LSP singlino-higgsino like**
- **LSP higgsino like**
- **LSP bino-higgsino like (Focus Point)**







Up to 60% enhancement in di-photon mode!



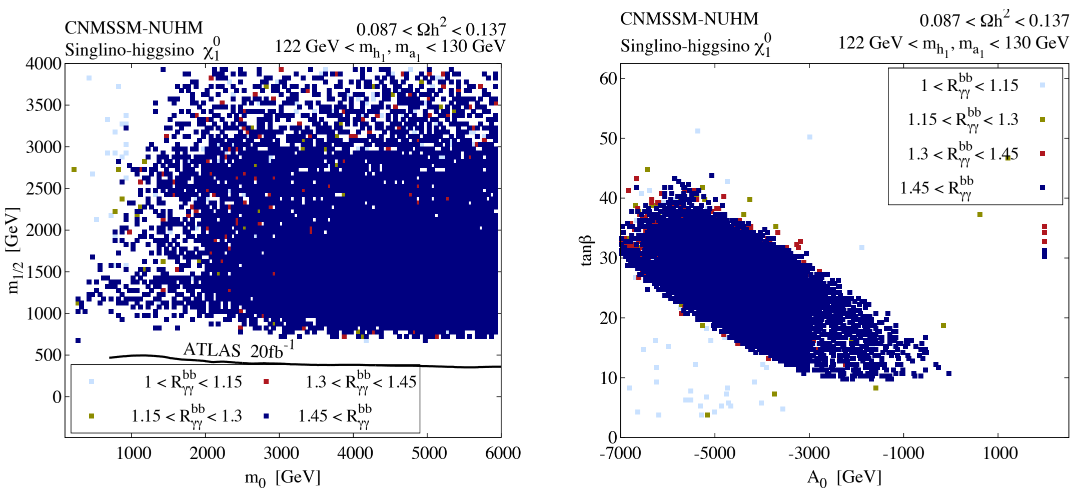
Bonus: significant enhancement also in bb and tau-tau decay modes (all the cases)

Need associated b-bbar-h production

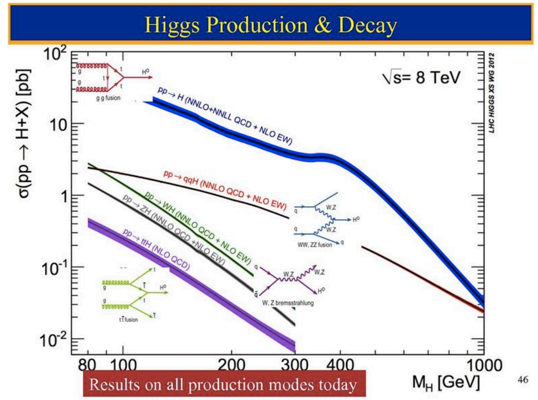
All this can be realized in associated bbar H production mode, and not gluon-fusion mode!

It is tiny in the SM, but tanb^2-enhanced in the MSSM.

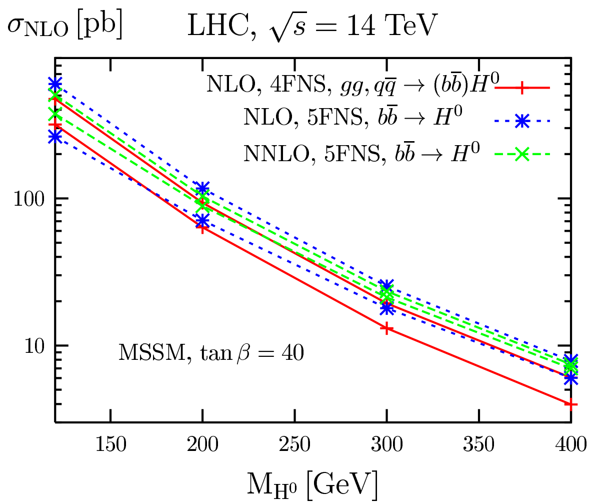
In all 3 cases, tan can be large, e.g.:



(V. Sharma)



Dawson, et al, 0508293



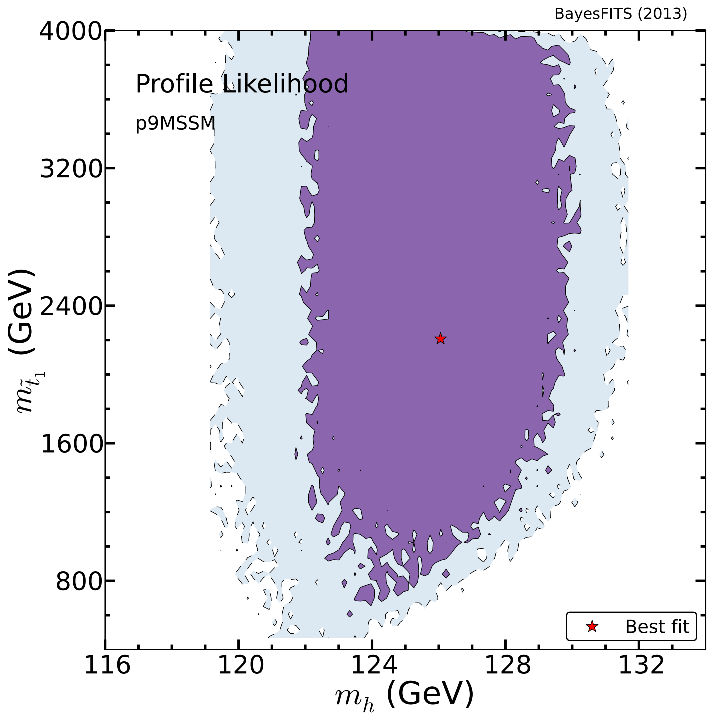
h1-a1 degeneracy ~126 GeV can be tested in bbbar h.
Signature: simultaneous di-photon, tau-tau, and bbbar
Enhancement in SM-subdominant mode

~126 GeV Higgs in general MSSM

- **More parameters, more freedom**

...here 9 parameters: p9MSSM

$$M_2,\ M_3,\ m_{\tilde{Q}_3},\ m_{\tilde{L}_3},\ A_t,\ A_\tau,\ m_A,\ \mu,\ \tan\beta$$



Parameter	Range
gluino mass	$0.7 < M_3 < 8$
wino mass	$0.01 < M_2 < 4$
bino mass	$M_1 = 0.5 M_2$
stop trilinear coupl.	$-7 < A_t < 7$
τ trilinear coupl.	$-7 < A_\tau < 7$
sbottom trilinear coupl.	$A_b = -0.5$
pseudoscalar mass	$0.2 < m_A < 4$
μ parameter	$0.01 < \mu < 4$
3rd gen. soft squark mass	$0.3 < m_{\tilde{Q}_3} < 4$
3rd gen. soft slepton mass	$0.1 < m_{\tilde{L}_3} < 2$
1st/2nd gen. soft slepton mass	$m_{\tilde{L}_{1,2}} = M_1 + 50\,\mathrm{GeV}$
1st/2nd gen. soft squark mass	$m_{\tilde{Q}_{1,2}} = 2.5$
ratio of Higgs doublet VEVs	$3 < \tan\beta < 62$
Nuisance parameter	Central value, error
Bottom mass $m_b(m_b)^{\overline{MS}}$ (GeV)	(4.18, 0.03)
Top pole mass M_t (GeV)	(173.5, 1.0)

~126 GeV Higgs still implies heavy, ~TeV-scale superpartners

...except for very fine tuned corners which allow much lighter staus, stops, charginos

p9MSSM: Constraints

Measurement	Mean or range	Error: exp., th.	Distribution
CMS α_T 11.7/fb , $\sqrt{s} = 8\,\text{TeV}$	See text.	See text.	Poisson
m_h (by CMS)	125.8 GeV	0.6 GeV, 3 GeV	Gaussian
$\Omega_\chi h^2$	0.1199	0.0027, 10%	Gaussian
$\text{BR}\left(\overline{B} \to X_s\gamma\right)\times10^4$	3.43	0.22, 0.21	Gaussian
$\text{BR}\left(B_u \to \tau\nu\right)\times10^4$	1.66	0.33, 0.38	Gaussian
ΔM_{B_s}	$17.719\,\text{ps}^{-1}$	$0.043\,\text{ps}^{-1}$, $2.400\,\text{ps}^{-1}$	Gaussian
$\sin^2\theta_{\text{eff}}$	0.23146	0.00012, 0.00015	Gaussian
M_W	80.399 GeV	0.023 GeV, 0.015 GeV	Gaussian
$\text{BR}\left(B_s \to \mu^+\mu^-\right)\times10^9$	3.2	+1.5, −1.2, 10%	Gaussian
$m_b(m_b)^{\overline{MS}}$	4.18 GeV	0.03 GeV, 0	Gaussian
M_t	173.5 GeV	1.0 GeV, 0	Gaussian
$\delta\,(g-2)_\mu^{\text{SUSY}}\times10^{10}$	28.7	8.0, 1.0	Gaussian
XENON100 (2012)	See text.	See text.	Poisson
CMS $3l + E_T^{\text{miss}}$ 9.2/fb, $\sqrt{s} = 8\,\text{TeV}$	See text.	See text.	Poisson

BASIC

Table 2: The experimental constraints that we include in our likelihood functions to constrain our p9MSSM model. We denote the first block of constraints as **basic**.

Now include (optionally) DM direct detection limit in the likelihood function

Plus LEP, Tevatron:

$$
\begin{aligned}
m_\chi &> 46\,\text{GeV},\\
m_{\tilde{e}} &> 107\,\text{GeV},\\
m_{\tilde{g}} &> 500\,\text{GeV},\\
m_{\chi_1^\pm} &> 94\,\text{GeV if } \mathrm{m}_{\chi_1^\pm} - \mathrm{m}_\chi > 3\,\text{GeV and } \tan\beta < 40\\
m_{\tilde{\mu}} &> 94\,\text{GeV if } \mathrm{m}_{\tilde{\mu}} - \mathrm{m}_\chi > 10\,\text{GeV and } \tan\beta < 40.\\
m_{\tilde{\tau}} &> 81.9\,\text{GeV if } \mathrm{m}_{\tilde{\tau}_R} - \mathrm{m}_\chi > 15\,\text{GeV},\\
m_{\tilde{b}_1} &> 89\,\text{GeV if } \mathrm{m}_{\tilde{b}_1} - \mathrm{m}_\chi > 8\,\text{GeV},\\
m_{\tilde{t}_1} &> 95.7\,\text{GeV if } \mathrm{m}_{\tilde{t}_1} - \mathrm{m}_\chi > 10\,\text{GeV}.
\end{aligned}
$$

Direct Detection of DM in MSSM

2D profile likelihood

(g-2)_muon not applied

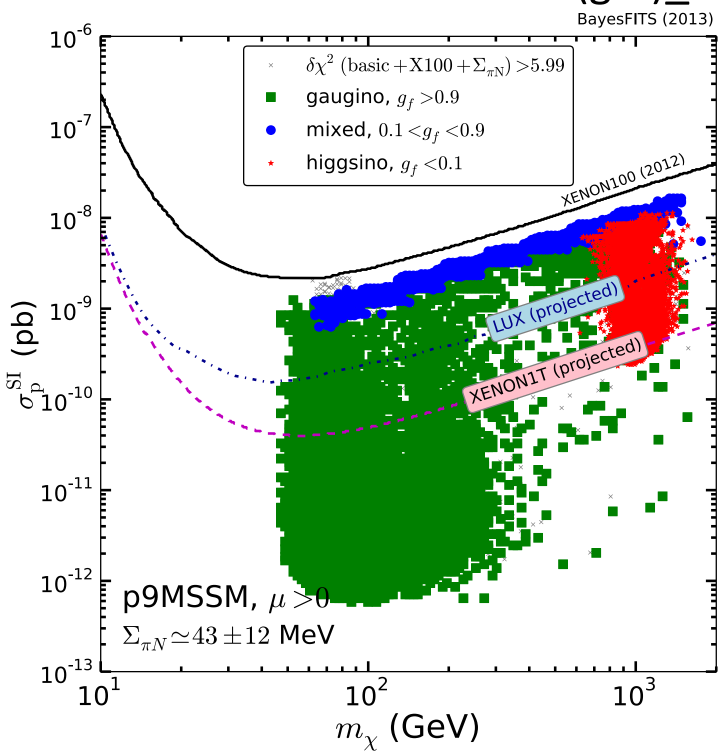
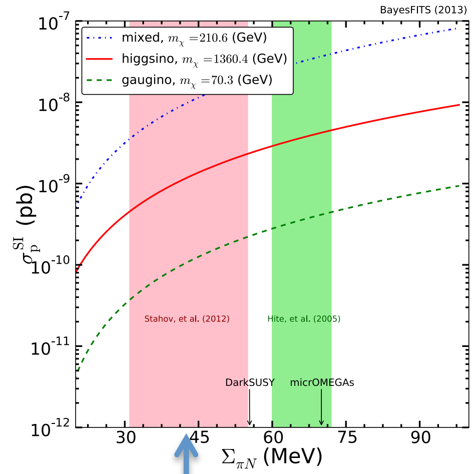


Figure 6: p9MSSM points that are allowed at 2σ by the **basic** constraints on the (m_χ, σ_p^{SI}) plane. The points consistent at 2σ with the **basic** *and* XENON100 constraints are divided by the composition of the neutralino: gaugino-like (green squares), mixed (blue circles), or higgsino-like (red stars). Points excluded at the 95% C.L. by **basic**+XENON100 are shown as gray crosses. (a) $\Sigma_{\pi N} \simeq 43 \pm 12$ MeV, (b) $\Sigma_{\pi N} \simeq 66 \pm 6$ MeV.

p9MSSM

arXiv:1306.1567



$$\Sigma_{\pi N} = 43 \pm 12\,\mathrm{MeV}$$

(new determination)

$$\Sigma_{\pi N} = \frac{m_u + m_d}{2}\langle N|\bar{u}u + \bar{d}d|N\rangle$$

Biggest uncertainty in DD c.s.

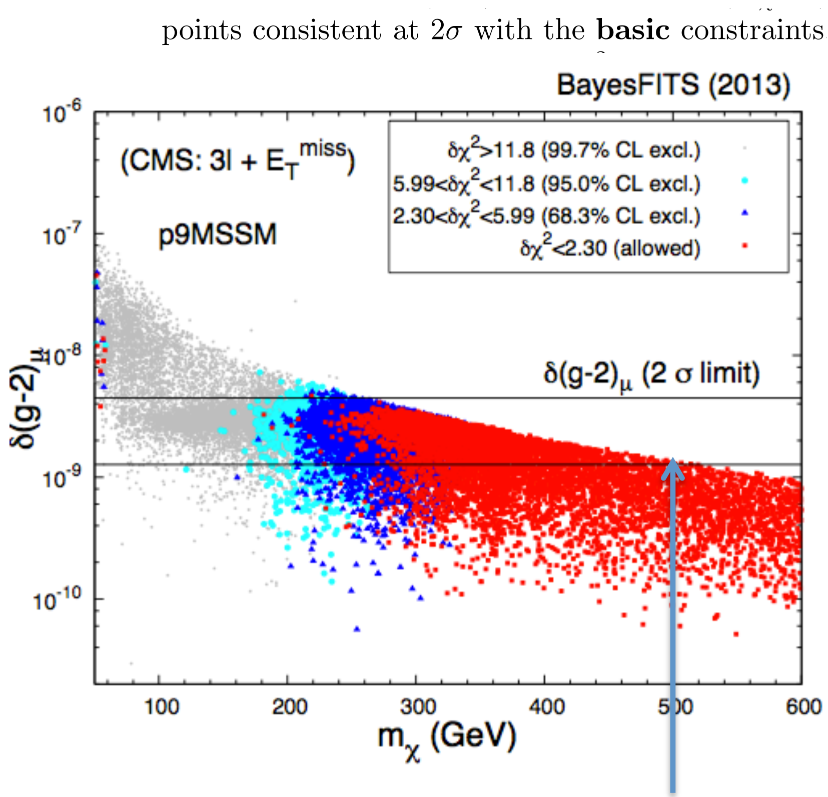
MSSM: signal likely but not guaranteed

(g-2) anomaly:

- **Inconsistent with SUSY with slepton-squark unfication**
- **Implies:**
  - m_chi~<500 GeV
  - smuon, sneutrino~<600 GeV

    (2sigma, p9MSSM)

Window of hope for LHC14



… a question on many people's mind…

But what about fine-tuning/naturalness?!

- I prefer to follow what the data implies, rather than theoretical prejudice
- Stabilizing mass hierarchy: initial motivation for SUSY but why should we treat it as a sacred cow

Initial motivation for cosmic inflation was to rid the Universe of unwanted relics like monopoles. Now: primordial density perturbation

- Naturalness: fundamental Higgs -> SUSY
- 126 GeV -> generically 1TeV <~ M_SUSY tens of TeV

- Fine-tuning is needed at any scale above the EW scale!

1 TeV is not a magic number

- If SUSY is discovered, large FT issue will have to be understood/accepted
- If SUSY is not discovered, the issue will become irrelevant
- Naturalness argument gone astray:

$$\frac{m_t}{m_b} \sim \frac{m_c}{m_s} \simeq 14 \;\Rightarrow\; m_t \simeq 60\,\mathrm{GeV}$$

To take home:

- Even the simplest constrained SUSY model CMSSM is consistent with all experimental constraints.

  except (g-2)_muon, R(gamma gamma)

  (Other simple constrained SUSY models: more freedom or similar story.)

- Higgs of 126 GeV --> typically M_SUSY at multi-TeV scale.

  Plus a window of light stop_1 (~1TeV) – best fit region (stau coann.)

- 1-tonne DM detectors to probe most CMSSM parameters.

  Big bite by LUX in 2014. Far beyond direct LHC reach.

  Other simple constrained SUSY models: similar story.

  MSSM: wide ranges within/outside 1-tonne detector’s reach.

- 1TeV (higgsino) LSP DM – generic prediction of constrained SUSY models (and also MSSM – but inconsistent with g-2!)
- MSSM: (g-2)_muon: some EWinos within ~500 GeV

- CNMSSM+NUHM: h1+a1 degeneracy: simultaneous enhancement of Higgs to 2-photon, tau-tau and bbar, but not ZZ, WW signal in (SM-subdominant) bbbar H mode

The real message:

SUSY may be too heavy for the LHC

Dark matter searches are likely to come to the rescue

BACKUP

High FT: problem or a hint?

- m_h~126 GeV -> M_SUSY ~> 1 TeV -> **high FT is basically ``an experimental fact''**

  …despite various ``islands'' of smaller M_SUSY here and there

- EWSB: $$\mu^2 = -\frac{1}{2}M_Z^2 + \frac{m_{H_d}^2(M_{\rm SUSY}) - \tan^2\beta\, m_{H_u}^2(M_{\rm SUSY})}{\tan^2\beta - 1}$$ $m_{H_{u,d}}^2$: tree + 1L corrs

- FT argument: $\boldsymbol{m_{H_u}^2,\ m_{H_u}^2}$ **and** $\boldsymbol{\mu^2}$ **need to be all fine-tuned to give** $\boldsymbol{M_Z^2}$

- Standard approach: look for ways to reduce it

- Another approach: accept it as an anthropic ``accident'' (Ibanez)

- **Our way: Do the regions favored by m_h~126 GeV and DM density map out certain relations at the GUT scale?**

Is nature telling us something?