Some lessons from Higgs boson and other LHC results for New Physics

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Many open questions in particle physics

- Origin of particle masses?
- Origin of EWSB?
- Origin and structure of flavor and CP X?
- New physics beyond the Standard Model?
- Dark matter in the Universe?
- Unification of fundamental forces?
- Role of gravity?
- History of the early Universe?
- …

LHC: chance to shed light on some of them

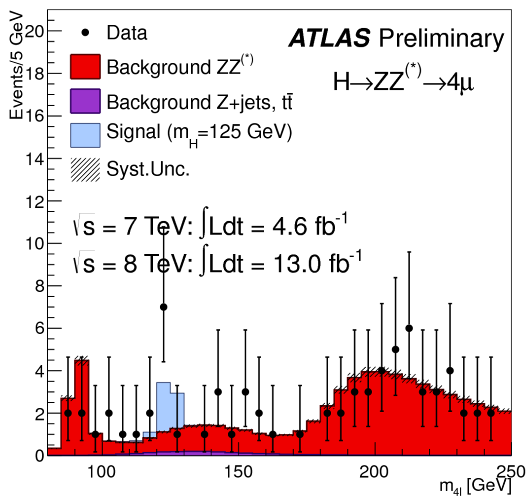
Many BSM ideas waiting to be tested…

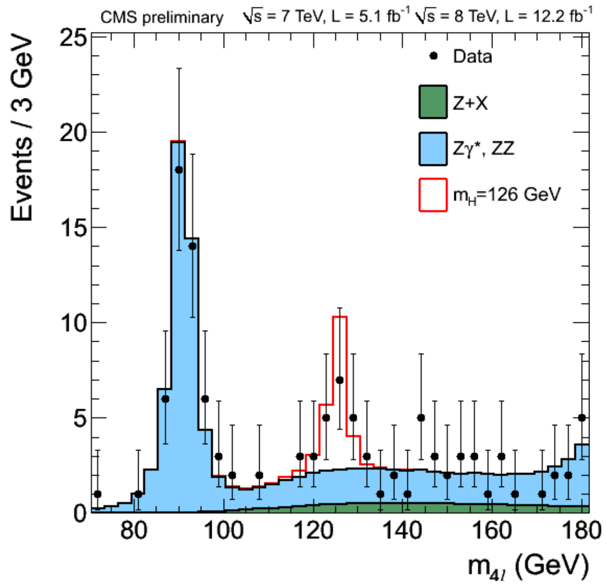
- Supersymmetry of several sorts
- Large/warped extra dimensions
- Low-scale gravity, microscopic black holes
- Little Higgs framework
- Extra gauge bosons
- Extra fermions
- Extra interactions
- …

Main news from the LHC so far…

…a BSM theorist's perspective!

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





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

$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.2^{+1.5}_{-1.2}) \times 10^{-9}$

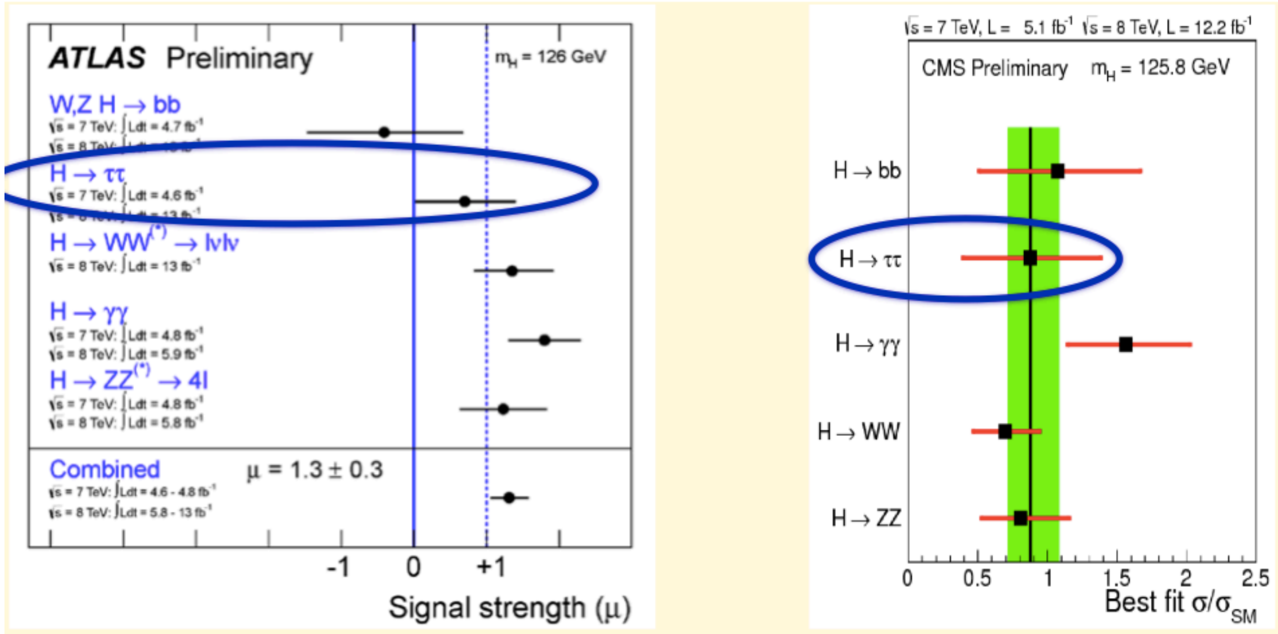
The Higgs boson!

- **First fundamental (?) spin-0 (?) state**
- **Validation of last 50 years of theory work**
- **Plan A confirmed (EWSB via Higgs mechanism)**

…with no real Plan B in the sleeve

Is the Higgs boson SM-like?

- **Possibly, not enough data and precision yet**



- **Enhancements/deficits real?**

Too early too tell. Current situation somewhat confusing. Many speculations, unlikely to pass the test of time.

Ways to go

- SM confirmed – end of the story (and collider physics?)
- Higs is fundamental - > SUSY
- Higgs is composite -> effective theory
- …

My approach in this talk:

Main interest: prospects to discover signatures at the LHC(14TeV)

Much less: theoretical and/or esthetic arguments (fine-tuning, naturalness, etc).

m_h~126 GeV

- **SM:** Higgs mass not predicted

m_h^2 = lambda * v^2

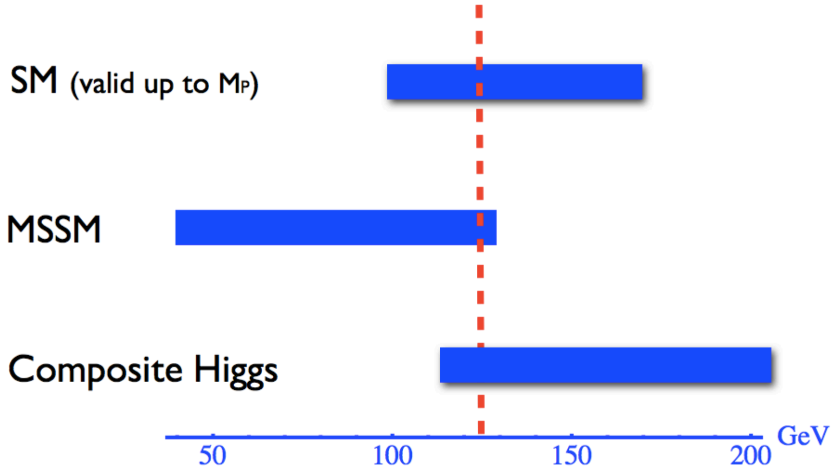
-> lambda ~0.25 – perturbative theory!

- **SUSY:**

m_h ~< 135 GeV

- **Composite Higgs:**

m_h ~> 110 GeV

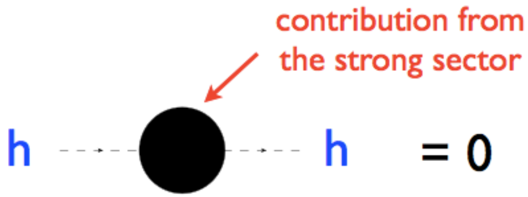


A. Pomarol

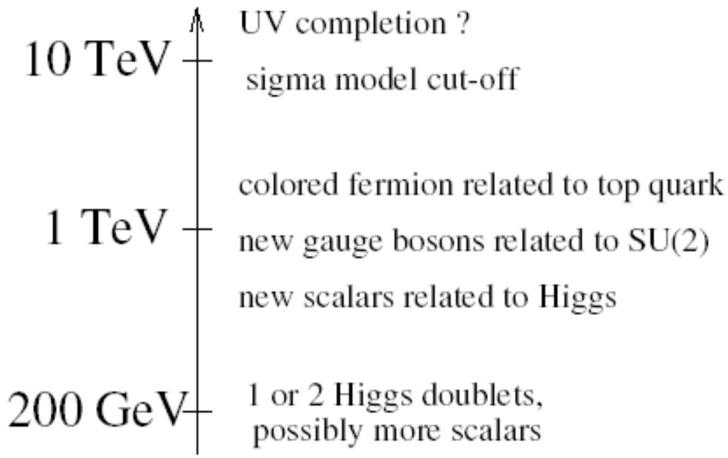
Higgs as a Pseudo-Goldstone Boson?

``Little Higgs'' models

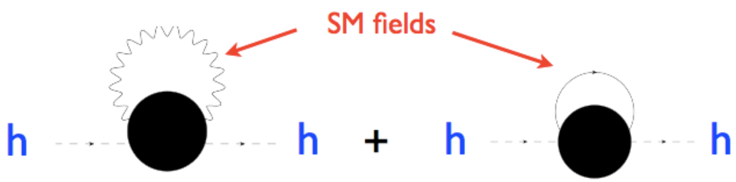
PGB: result of breaking of a global symmetry



=> Goldstone boson



SM couplings break global symmetry => PGB



New vector-like fermions
With EM charges of 5/3, 2/3, -1/3

Possible signature: same-sign dileptons

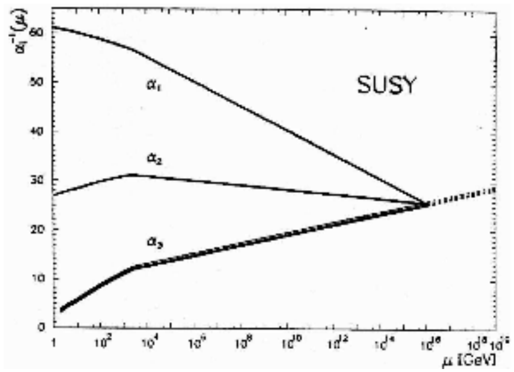
LH: Strong sector => hard to make predictions

Current limits: ~500-700 GeV

Supersymmetry

particle physics

- grand unification,
- supergravity, superstrings,
- hierarchy/naturalness/fine-tuning,
- fermion masses and mixings,
- neutrino masses and mixings,
- CP/flavor violation,
- . . .



astroparticle physics

- WIMP dark matter,
- E–WIMPs: gravitinos and axinos
- other relics

particle cosmology

- cosmic inflation,
- baryogenesis/leptogenesis,
- relic production and decay after BB,
- effect on and constrains from BBN,
- effect on and constrains from CMB,
- . . .

SUSY has dominated theoretical efforts beyond the SM for the last two-three decades. . .

Claims about SUSY

WRONG

- **SUSY can explain everything**
  (Eg. 135 GeV gamma line from GC)
- **SUSY has been discovered!**
- **SUSY has been ruled out!**

RIGHT

- **SUSY cannot be ruled out. It can only be discovered…**
  (… or abandoned)
- **Motivation for SUSY has become stronger**
  Light Higgs!

SUSY is not only shy but probably also heavy (~1 TeV)

~126 GeV Higgs and SUSY

- 1 loop correction

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

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

Sufficient to take large enough M_SUSY and/or adjust X_t

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

Can one have ~126 GeV Higgs in unified SUSY?

… with M_SUSY \lsim 1 TeV?

… and with other constraints satisfied?

Hide and seek with SUSY

SUSY can (potentially) contribute to various measurable quantities

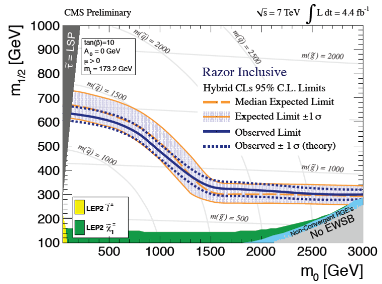
- signals of supersymmetric and Higgs particles

  direct collider searches: still only lower bounds on masses

- indirect (e.g. loop) contributions
  - electroweak observables: $\sin\theta_W, m_Z, \Gamma_Z$, ...
  - flavor processes: $b \to s\gamma$, $\mathrm{BR}(\bar{B}_s \to \mu^+\mu^-)$, $\mathrm{BR}(\overline{B}_u \to \tau\nu)$, ...
  - anomalous magnetic moment of the muon $(g-2)_\mu$
  - ...
- neutralino WIMP as dark matter to give correct relic abundance $\Omega_\chi h^2$

SUSY: most important constraints:

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



- **Direct search limits** — Lower limit…

- **The Higgs mass**
  - **ATLAS: m_H = 126.0±0.4(stat)±0.4(sys)**
  - **CMS: m_H =** 125.8 ± 0.4(stat) ± 0.4 (syst) GeV

- **B_s -> mu mu**
  - **LHCb:** $\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.2^{+1.5}_{-1.2})\times 10^{-9}$

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

- **(g-2)_muon**

The Likelihood function

Central object: Likelihood function

Positive measurements:

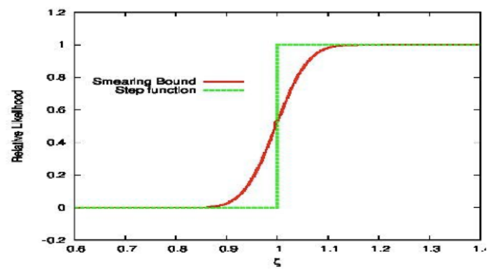
Take a single observable $\xi(m)$ that has been measured (e.g., M_W)

- 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.

Hide and seek with SUSY

Measurement	Mean or Range	Exp. Error	Th. Error	Distribution
CMS razor 4.4/fb analysis	See text	See text	0	Poisson
SM-like Higgs mass m_h	125.3	0.6	2	Gaussian
$\Omega_\chi h^2$	0.1120	0.0056	10%	Gaussian
$\sin^2\theta_{\mathrm{eff}}$	0.23116	0.00013	0.00015	Gaussian
m_W	80.399	0.023	0.015	Gaussian
? → $\delta\,(g-2)_\mu^{\mathrm{SUSY}} \times 10^{10}$	28.7	8.0	1.0	Gaussian
$\mathrm{BR}\left(\overline{\mathrm{B}} \to \mathrm{X_s}\gamma\right) \times 10^4$	3.60	0.23	0.21	Gaussian
$\mathrm{BR}\left(\mathrm{B_u} \to \tau\nu\right) \times 10^4$	1.66	0.66	0.38	Gaussian
ΔM_{B_s}	$17.77\,\mathrm{ps}^{-1}$	$0.12\,\mathrm{ps}^{-1}$	$2.40\,\mathrm{ps}^{-1}$	Gaussian
$\mathrm{BR}\left(\mathrm{B_s} \to \mu^+\mu^-\right)$	$(3.2^{+1.5}_{-1.2}) \times 10^{-9}$		11%	Gaussian

New!

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

10 dof

Constrained Minimal Supersymmetric Standard Model (CMSSM)

Kane, Kolda, Roszkowski and Wells, Phys. Rev. D 49 (1994) 6173

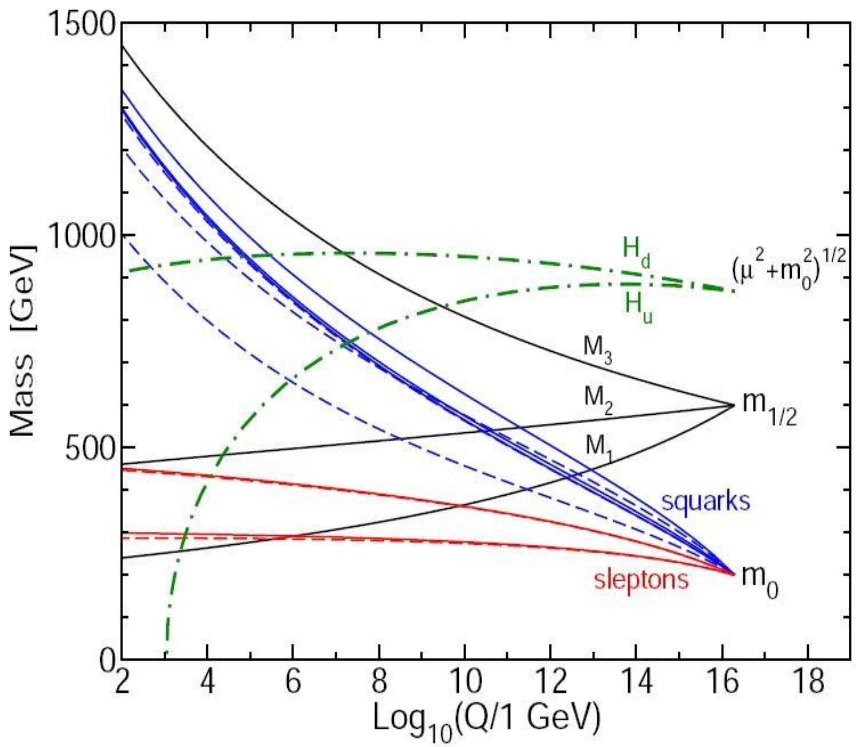


figure from hep-ph/9709356

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

- 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:
  $m_{1/2},\ m_0,\ A_0,\ \tan\beta,\ \mathrm{sgn}(\mu)$
- well developed machinery to compute masses and couplings

Light Higgs mass and SUSY

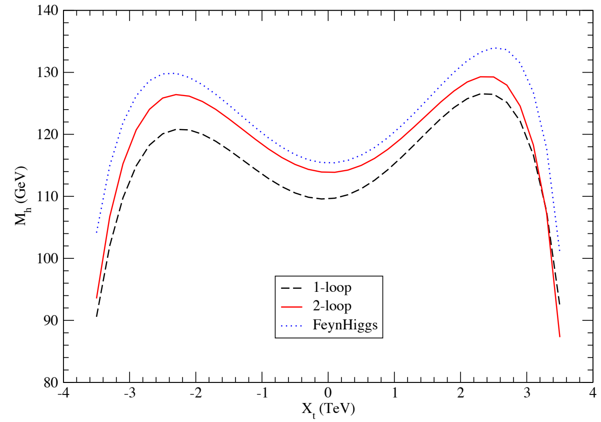
Djouadi, arXiv:hep-ph/0503173

- **In SUSY m_h is a calculated quantity.**
- **1-loop:** $\Delta m_h^2 = \frac{3m_t^4}{4\pi^2 v^2}\left[\ln\left(\frac{M_{\rm SUSY}^2}{m_t^2}\right) + \frac{X_t^2}{M_{\rm SUSY}^2}\left(1 - \frac{X_t^2}{12 M_{\rm SUSY}^2}\right)\right]$

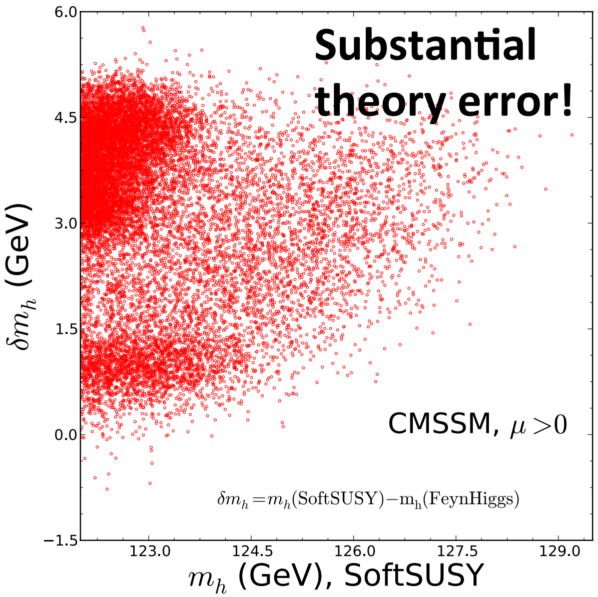
$$M_{\rm SUSY} \equiv \sqrt{m_{\tilde t_1} m_{\tilde t_2}}$$

- **2-loop:** DR-bar (Slavich,…) used in SoftSusy, Spheno, Suspect, and on-shell (Hollik,…) in FeynHiggs

differ by a few GeV



$$\text{maximal mixing scenario} : \quad X_t = A_t - \mu\cot\beta \sim \sqrt{6}\, M_S$$



Top (pole) mass:

- Tevatron combo 2012: 173.18 pm 0.56 pm 0.75 GeV
- LHC 2012 173.3 pm 0.5 pm 1.3 GeV
- PDG 2012: 173.5 pm 1.0 GeV
- CDF (16 may 2012) 173.9 pm 1.9 GeV

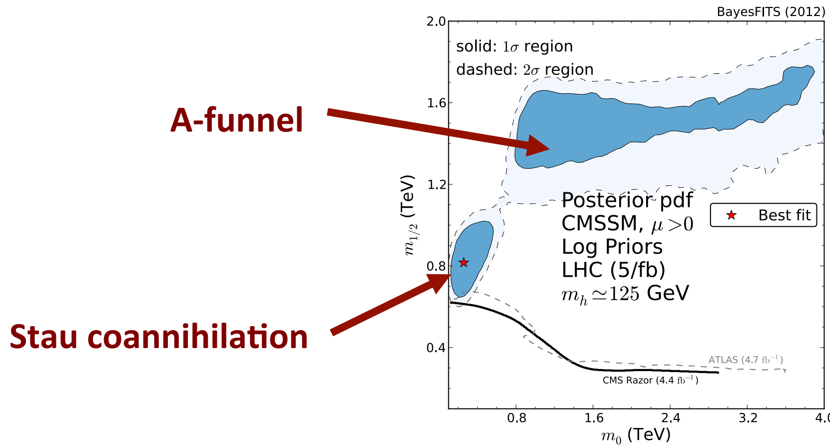
To maximize m_h:
-> increase M_SUSY, or
-> take large |X_t|~|A_t|

Higgs mass in the CMSSM

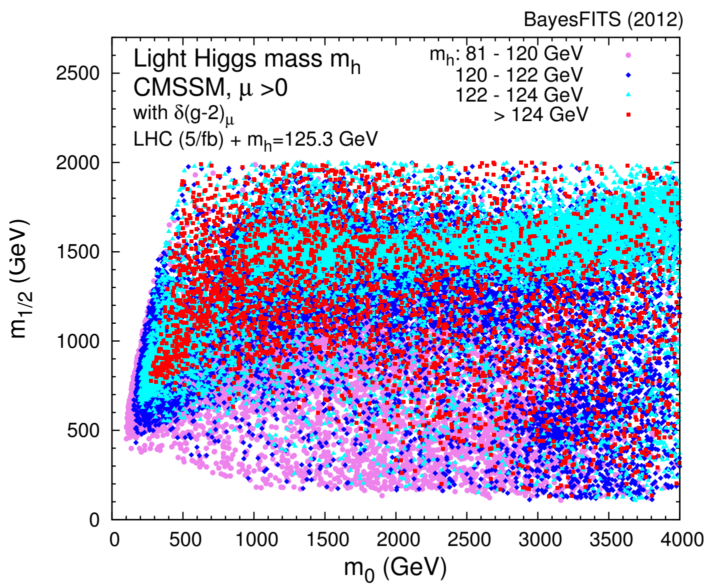
Likelihood fn

$$\mathcal{L}_{\rm mass} \sim e^{-\frac{(m_h - 125.3\ {\rm GeV})^2}{\sigma^2 + \tau^2}}$$

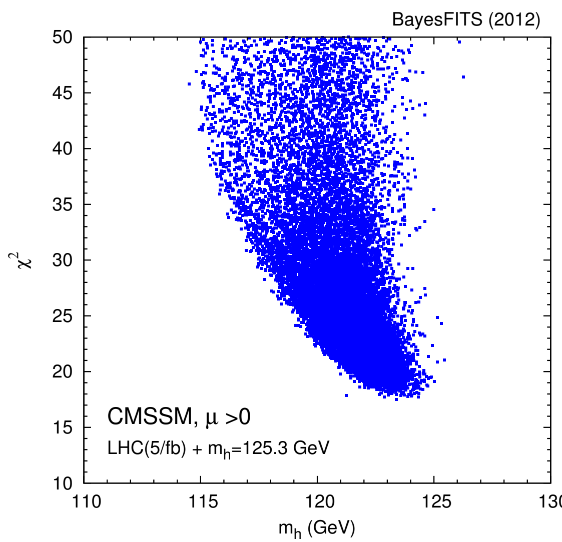
$$\sigma = 0.6\ {\rm GeV}, \tau = 2\ {\rm GeV}$$



Unified SUSY: m_h~125 GeV typically a bit too high (unless M_SUSY >> 1TeV)

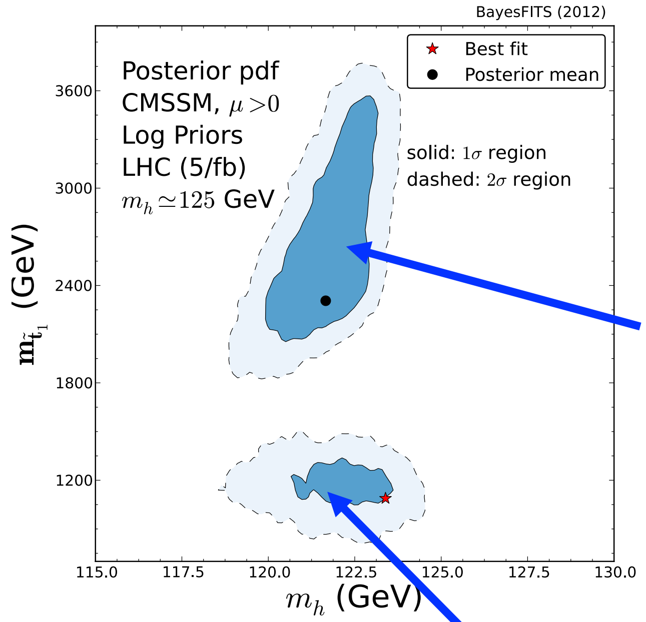


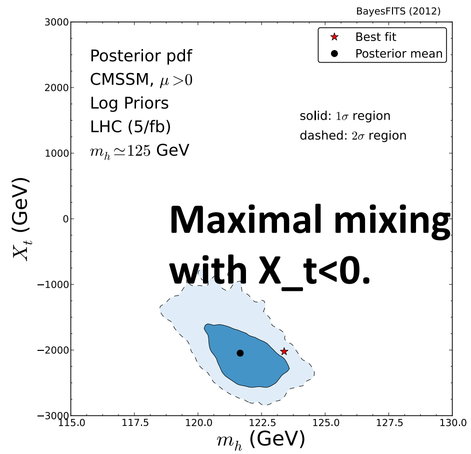
All relevant constraints included



~125 GeV Higgs near lowest chi2 (SC,AF)

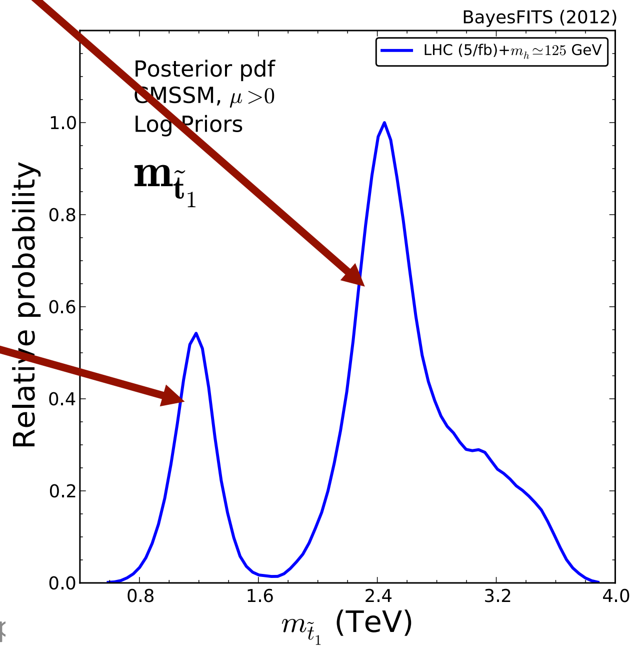
Higgs vs stop sector





A-funnel

Stau coannihilation



→ **Stop mass of ~1 TeV favored.**

Window of opportunity for LHC(14TeV)?

Beyond the Constrained MSSM

Less constrained unified SUSY models:

- **Add Higgs singlet (CNMSSM)**

  => very CMSSM-like

- **Relax Higgs mass unification (NUHM)**

  => slight increase in max m_h

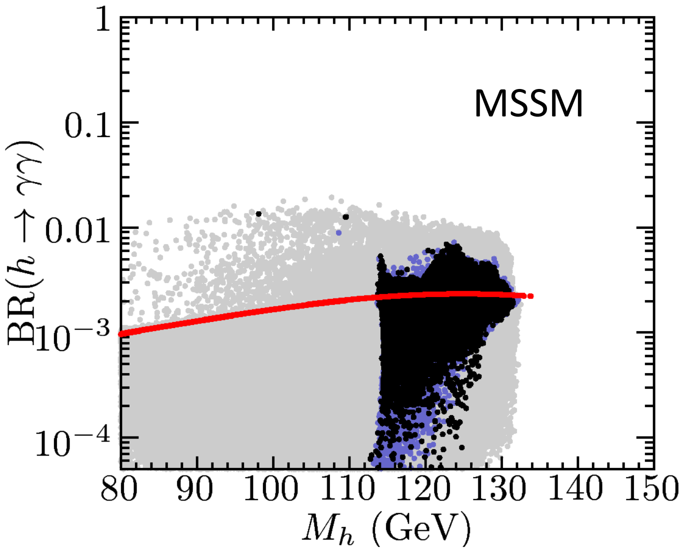
- **…**

Generally in unified SUSY: no enhancement in gamma-gamma!

SUSY at the EW scale (MSSM, NMSSM…):

=> easy to generate m_h~126 GeV

..and also gamma-gamma enhancement



Benbrik, et al., 1207.1096

But less motivated.

To summarize: 126 GeV Higgs and SUSY

Light Higgs m_h~126 GeV:

either

- **M_SUSY>> 1 TeV => bad news for the LHC?**

or

- **`light' stop of ~ 1 TeV, or even less => window for LHC**

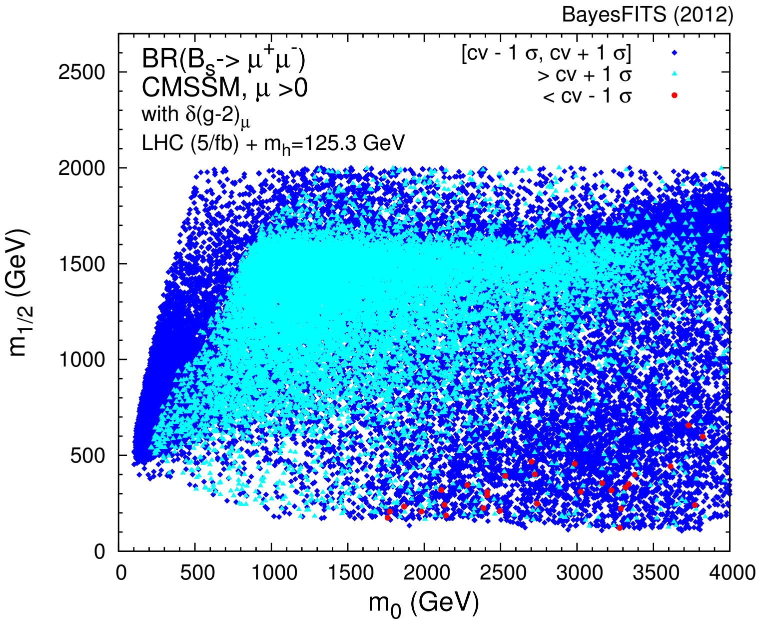
- **(Simplest) unified SUSY: tightly constrained; only few specific regions allowed by all relevant constraints**

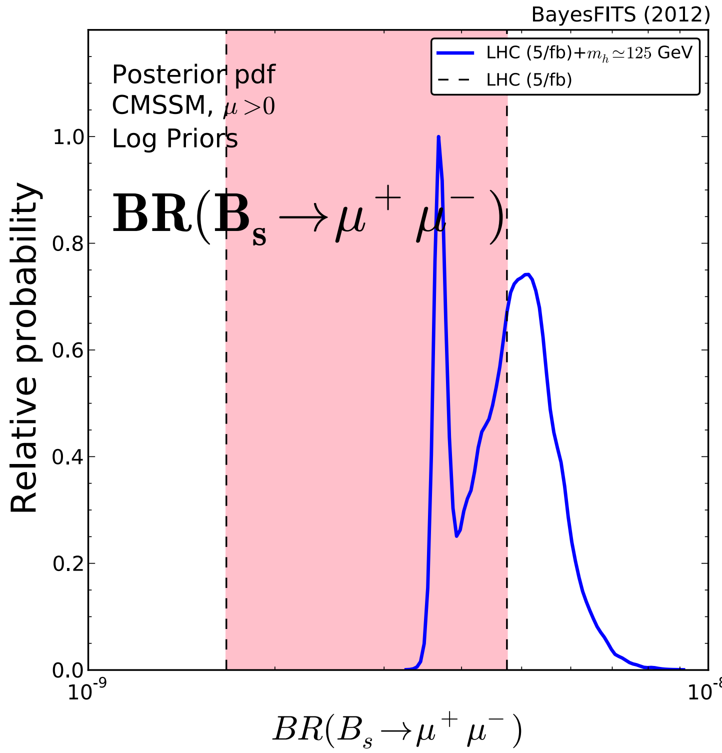
To be partly explored at LHC(14TeV) and in DM searches

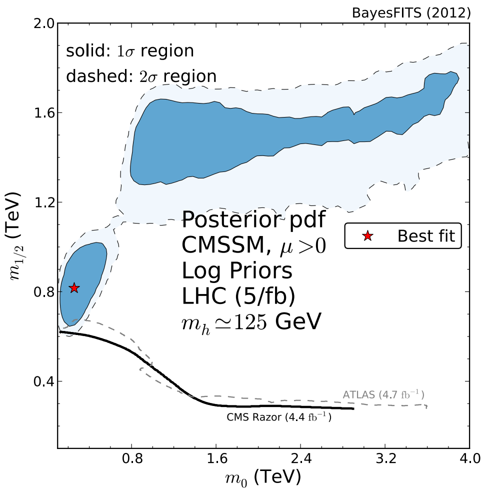
- **General MSSM and such: lots of room, much weaker bounds on superpartners (below ~1 TeV)**

- **Some speculations about heavy Higgs at 126 GeV, two Higgs degenerate in mass, etc: long shot, partly inconsistent with LHC and DM limits.**

CMSSM: Impact of BR(Bs->mu mu)







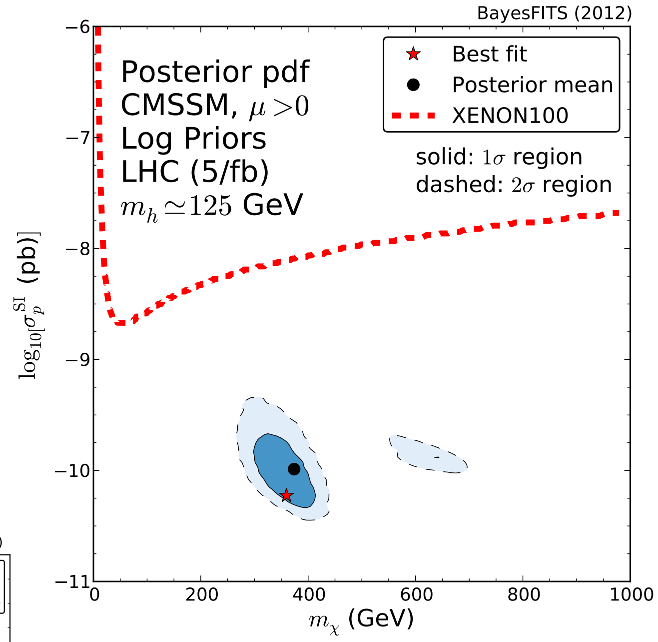
Consistent with the stau coannihilation region.
The A-funnel region slightly disfavored.

Abreu, et al.
BayesFITS (in prep.)

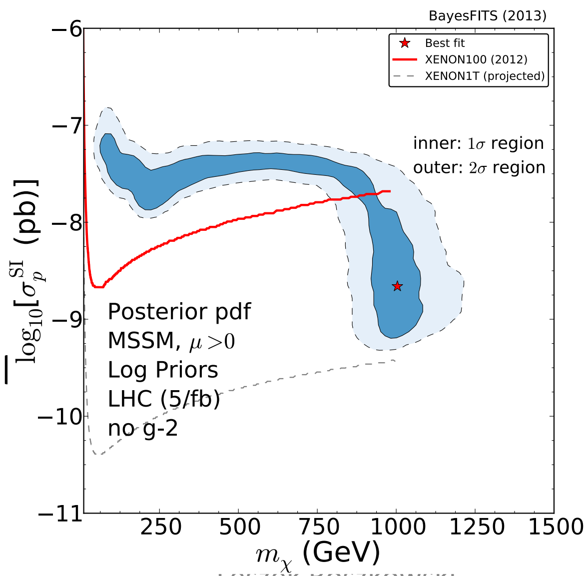
Direct detection of DM

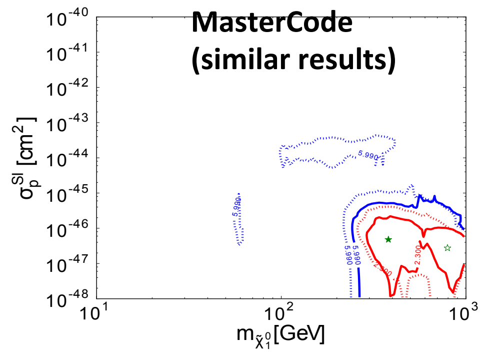
LHC limits on SUSY have pushed sigma_p down, well below current XENON100 limit.

One will need 1 tonne DM detectors to probe favored ranges.



(One-tonne detector reach: sigma_p~< few x10^-11 pb.)





General MSSM:

Larger sigma_p allowed but still need 1 tonne detectors to probe most ranges

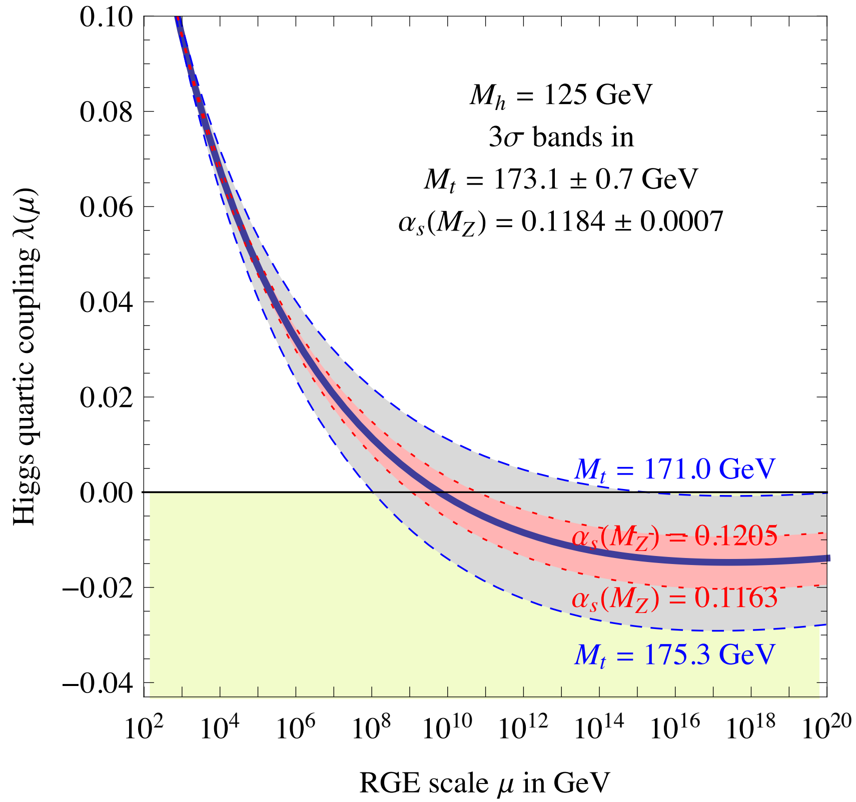
Higgs Mass and Vacuum Stability

Standard Model:

m_h^2 = lambda * v^2

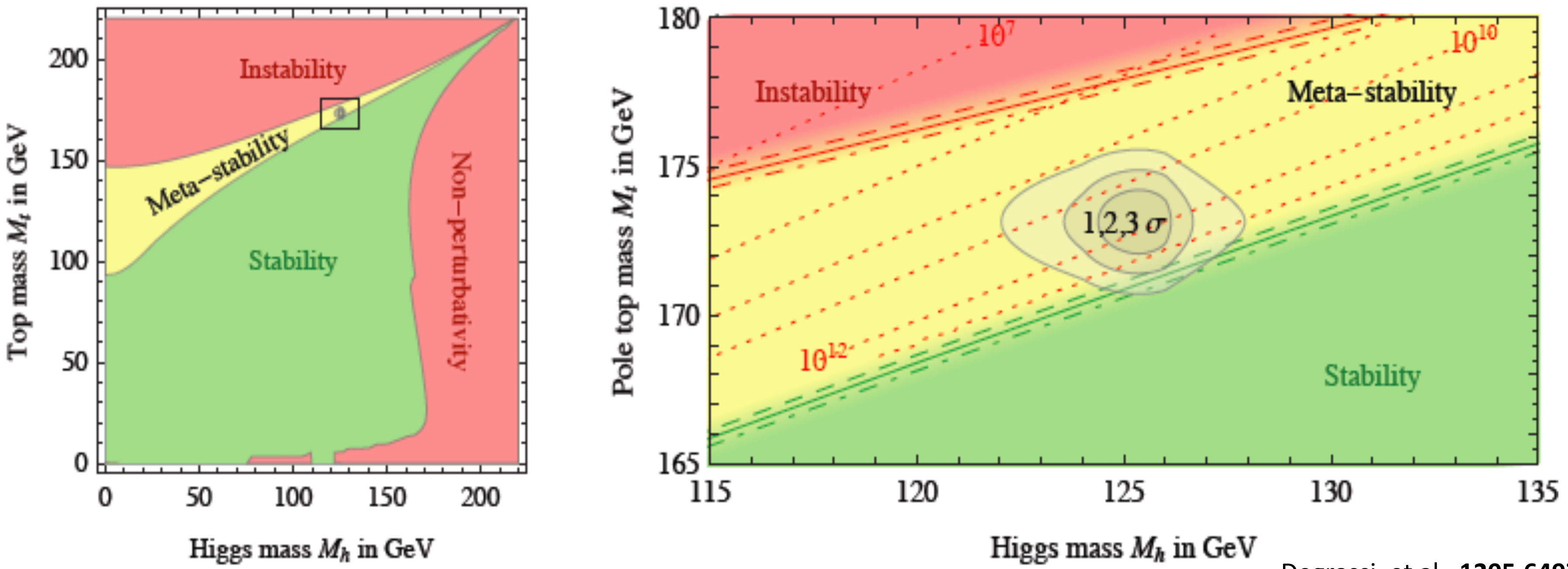
m_h~ 126 GeV
=> lambda ~0.25

small Higgs self-coupling: loop effects due to t-quark drive quartic coupling < 0 at some scale mu



Degrassi, et al., **1205.6497**

Higgs Mass and Vacuum Stability



Degrassi, et al., **1205.6497**

Standard Model: 125 GeV Higgs => Vacuum metastable?
(lifetime >> age of the Universe)

SUSY can stabilize it

The LHC era has only just begun…

- Simplest unified SUSY models under some pressure for M_SUSY~<1 TeV

- Much more room (below 1 TeV) in SUSY at the EW scale

- Generally m_h~126 GeV implies large scale of new physics (partly beyond the reach of LHC(14 TeV) but pockets of lighter mass spectra remain in many BSM models

- Some cleaing up has also begun:

E.g. spin-2 boson with graviton-like couplings (in warped extra dimension of AdS type) inconsistent with measured couplings to vector-boson pairs (WW, gamma-gamma)

Ellis, et al., 1211.3068

Gazing into a crystal ball...

We need more data!