Karlsruhe Institute of Technology, 16 January '12

Particle Physics and the first LHC results

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Roma Tre/CERN

In honour of Julius Wess

Julius Wess

A great man
A superb scientist
A friend

The first great result is that the LHC has worked very well in 2011!

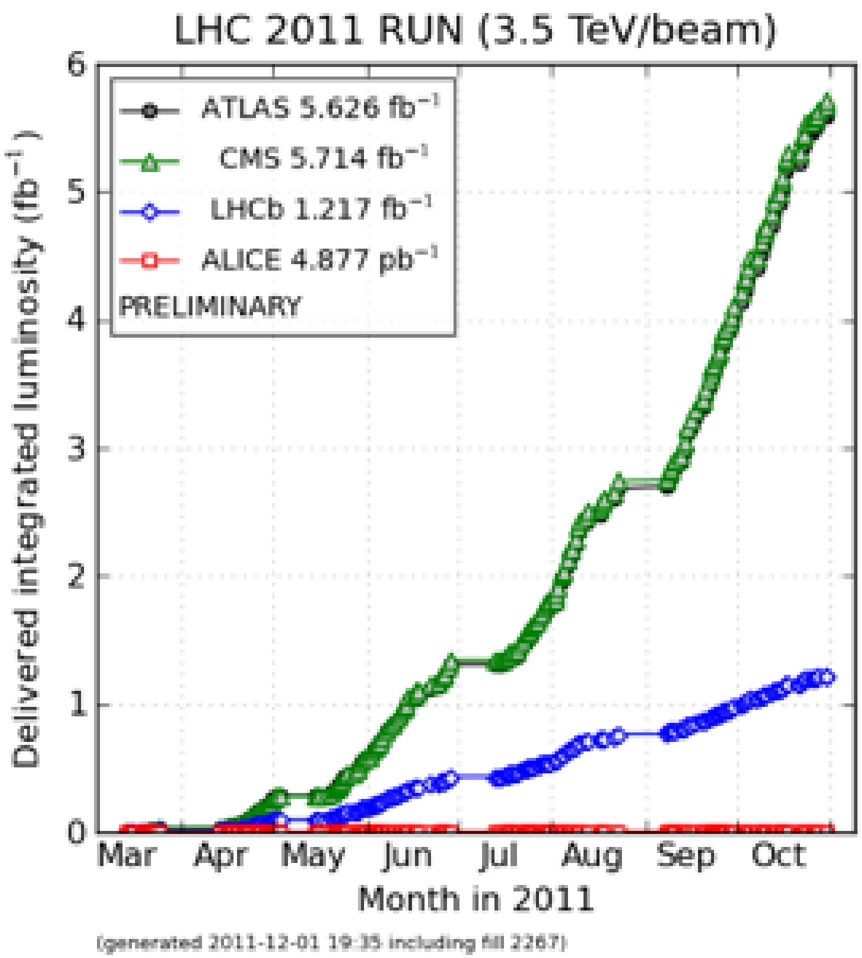
ATLAS&CMS

~5.6 fb^{-1} each

The target of 5 fb^{-1} for 2011 has been largely achieved!!

LHCb

~1.2 fb^{-1}



This is great news for particle physics !!

The Standard Model cannot be the whole story

The SM is a low energy effective theory
(nobody can believe it is the ultimate theory)

It happens to be renormalizable and highly predictive.
And is (too) well supported by the data.

But even just as a low energy effective theory
the SM is not satisfactory

In fact it is not completely verified: its simplest Higgs sector is so far only a conjecture and is problematic

and we expect New Physics at higher energies

not only from the GUT or Planck scales
but also from the TeV scale (LHC!)
hierarchy, dark matter...

The Higgs problem is central in particle physics today

The main problems of the SM show up in the Higgs sector

$$V_{Higgs} = V_0 - \mu^2 \phi^\dagger \phi + \lambda \left(\phi^\dagger \phi\right)^2 + [\bar{\psi}_{Li} Y_{ij} \psi_{Rj} \phi + h.c.]$$

Vacuum energy
$V_{0exp} \sim (2.10^{-3}\ \mathrm{eV})^4$

Origin of quadratic
divergences.
Hierarchy problem

Possible instability
depending on m_H

The flavour problem:
large unexplained ratios
of Y_{ij} Yukawa constants

That some sort of spontaneous symmetry breaking mechanism is at work has already been established (couplings symmetric, spectrum totally non symmetric)

The question is on the nature of the Higgs mechanism/particle(s)

- One doublet, more doublets, additional singlets?
- SM Higgs or SUSY Higgses
- Fundamental or composite (of fermions, of WW....)
- Pseudo-Goldstone boson of an enlarged symmetry
- A manifestation of extra dimensions (fifth comp. of a gauge boson, an effect of orbifolding or of boundary conditions....)
- Some combination of the above

Alternative forms of EW symmetry breaking
A vast literature

Examples:

- SUSY Higgs
- Little Higgs
- Higgs from Extra Dim's
- Higgsless models
- Composite Higgs
- • • •

Except for SUSY,
common ingredients are:
the Higgs is a pseudo
Goldstone boson of an
enlarged symmetry --->
new vector bosons

Z', W', ρ'...

Non perturbative sectors
limit predictivity and
all need
an UV completion

Crosstalk with string theory:

Extra dimensions (large, warped), branes,
AdS/CFT correspondence

Can we do without the Higgs?

Suppose we take the gauge symmetric part of the SM and put masses by hand.

Gauge invariance is broken explicitly. The theory is no more renormalizable. One loses understanding of the observed accurate validity of gauge predictions for couplings.

Still, what is the fatal problem at the LHC scale?

The most immediate disease that needs a solution is the occurrence of unitarity violations in some amplitudes

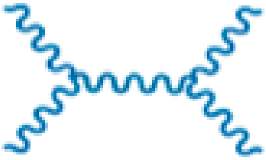
With no Higgs unitarity violations for E_{CM} ~ 1-3 TeV

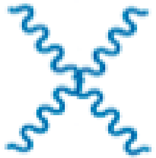
Unitarity implies that scattering amplitudes cannot grow indefinitely with the centre-of-mass energy s

In the SM, the Higgs particle is essential in ensuring that the scattering amplitudes with longitudinal weak bosons (W_L , Z_L) satisfy (tree-level) unitarity constraints
[Veltman, 1977; Lee-Quigg-Thacker, 1977; . . .]

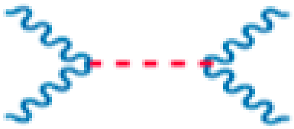
Zwirner

An example: $\mathcal{A}(W_L^+ W_L^- \longrightarrow Z_L Z_L) \quad (s \gg m_W^2)$





$$i\frac{s}{v^2}$$



$$-i\frac{s^2}{v^2(s-m_h^2)}$$

$$\rightarrow \quad -i\frac{m_h^2}{v^2}\frac{s}{s-m_h^2}$$

If no Higgs then something must happen!

Can we do without the Higgs?

Suppose we take the gauge symmetric part of the SM and put masses by hand.

Gauge invariance is broken explicitly. The theory is no more renormalizable. One loses understanding of the observed accurate validity of gauge predictions for couplings.

Still, what is the fatal problem at the LHC scale?

The most immediate disease that needs a solution is the occurrence of unitarity violations in some amplitudes

To avoid this either there is one or more Higgs particles or some new states (e.g. new vector bosons)

Thus something must happen at the few TeV scale!!

A crucial question for the LHC

What saves unitarity?

- the Higgs
- some new vector boson

  W′, Z′
  KK recurrences
  resonances from a strong sector
  ......

The main LHC results so far

- A robust exclusion interval for the SM Higgs.

Only a narrow window is left below 600 GeV:
115.5-127 GeV.

ATLAS, CMS

Plus some indication for m_H ~ 125 GeV

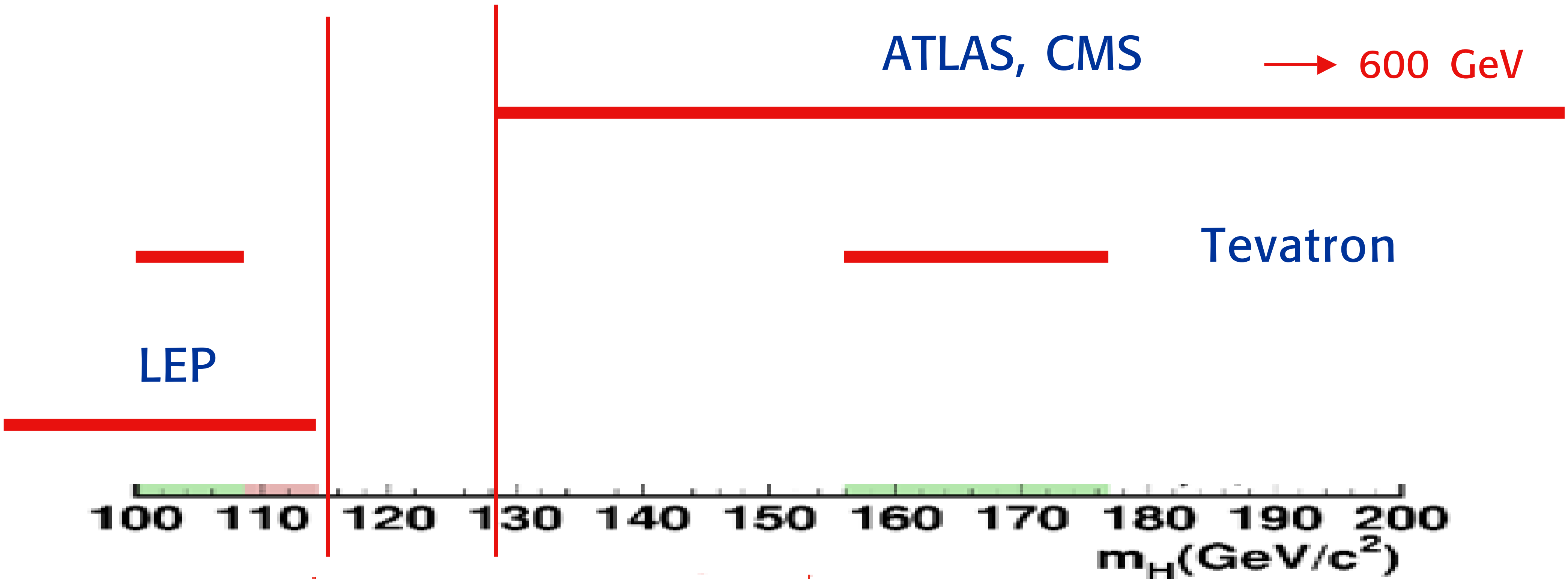
- No evidence of new physics, althouh a big chunk of new territory has been explored

- Important results on B and D decays from LHCb

[e.g. B_s->$J/\Psi\phi$, B_s->$\mu\mu$, ... CP viol in D decay]

- Two heavy ion runs so far (ALICE)
- Forward pp physics (TOTEM)

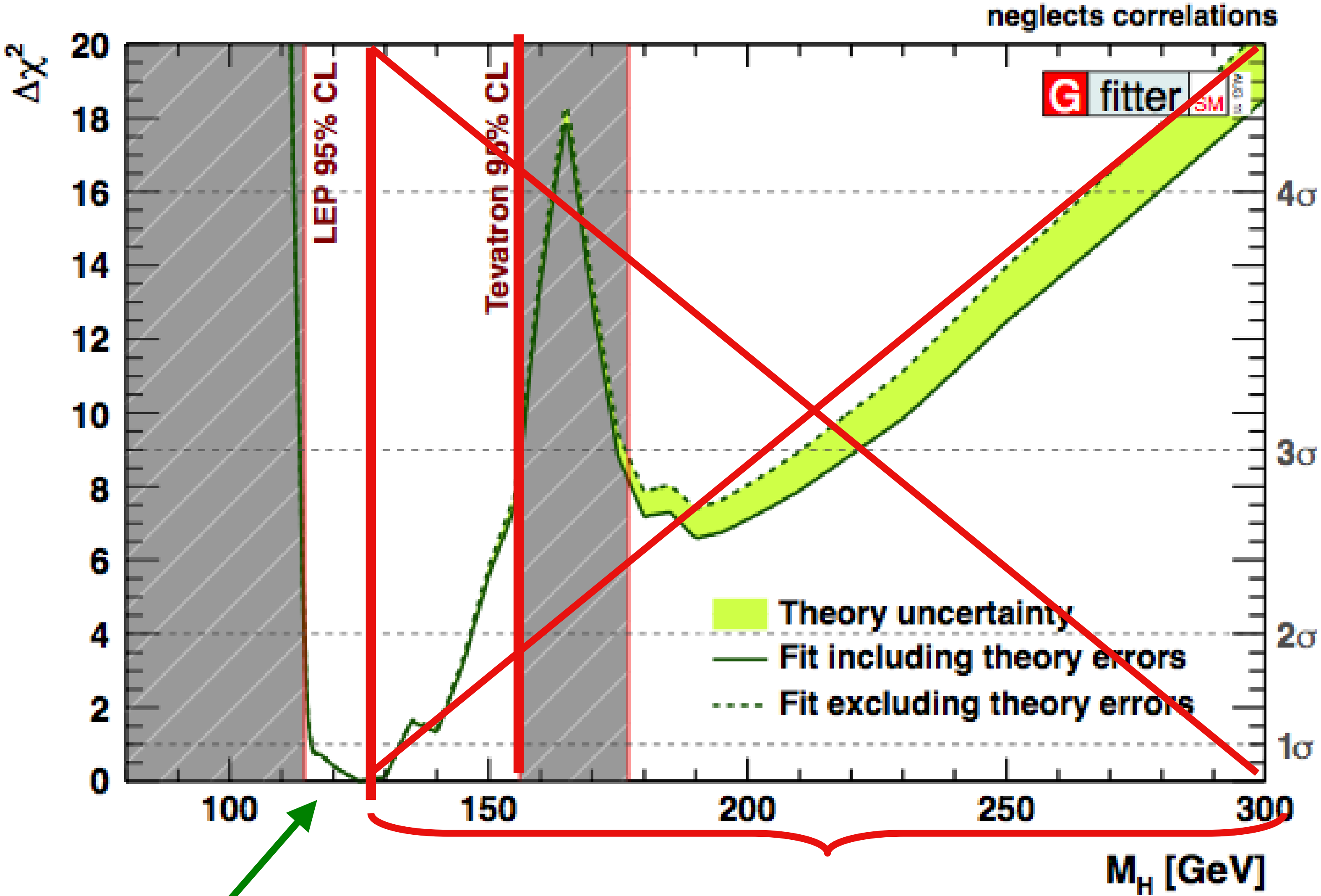
The 95% exclusion intervals for the light Higgs



115.5-127 GeV

The window of opportunity

$m_H > 600$ GeV
also allowed



A light SM Higgs can only be in 115.5-127 GeV range, in agreement with EW tests

Excl. by ATLAS and/or CMS

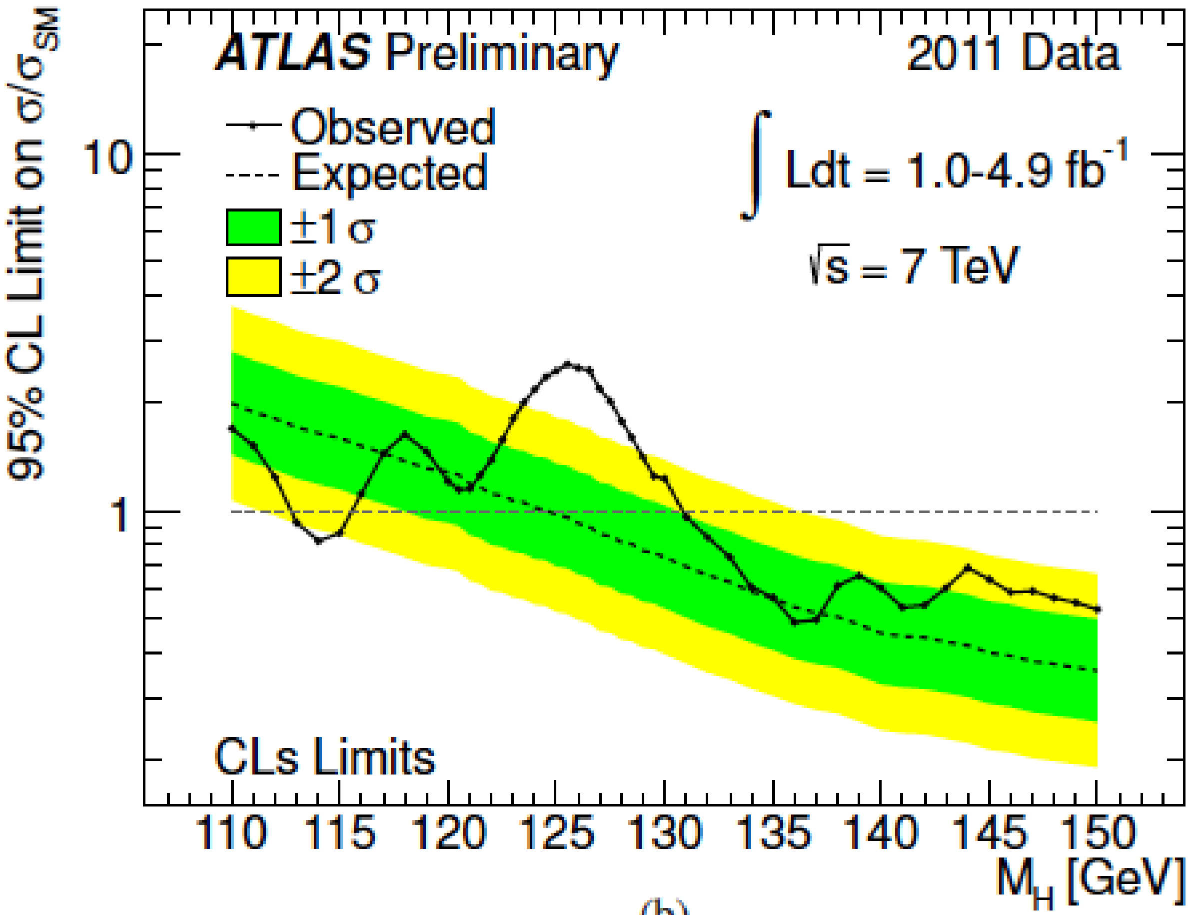
also $300 < m_H < 600$ GeV is excluded

Some “excess” was reported in the allowed m_H window

Is this the Higgs signal?

We hope yes, but the present evidence could still evaporate with more statistics

We need to wait for the 2012 run



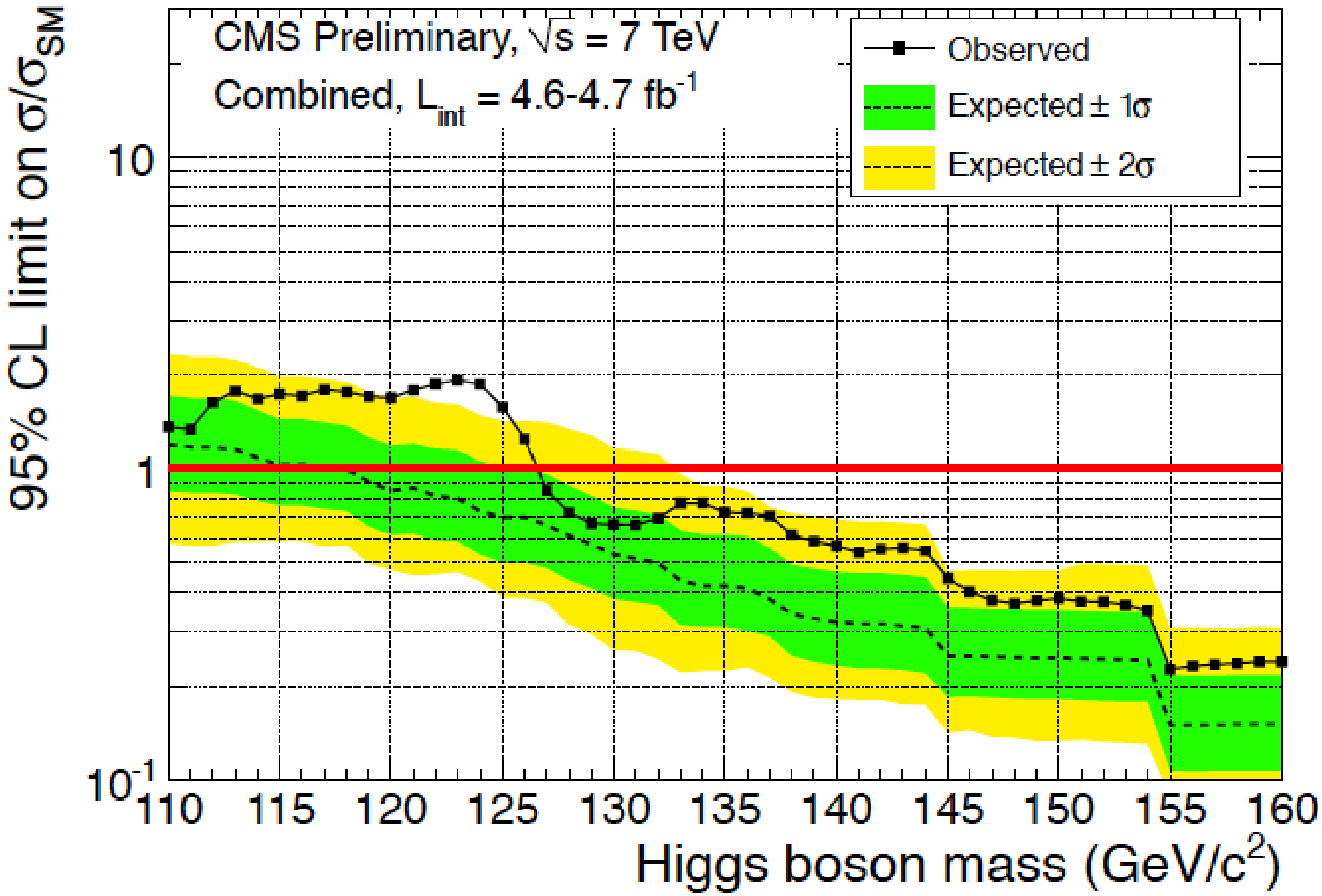
(b)

Observed excess over SM for m_H ~ 126 GeV in:
H->$\gamma\gamma$ (2.8σ), H->ZZ*->4$l^{\pm}$ (2.1σ), H->WW*-> $l\nu l\nu$ (1.4σ).

Combined: 3.6σ (but with look-elsewhere-effect 2.3σ)

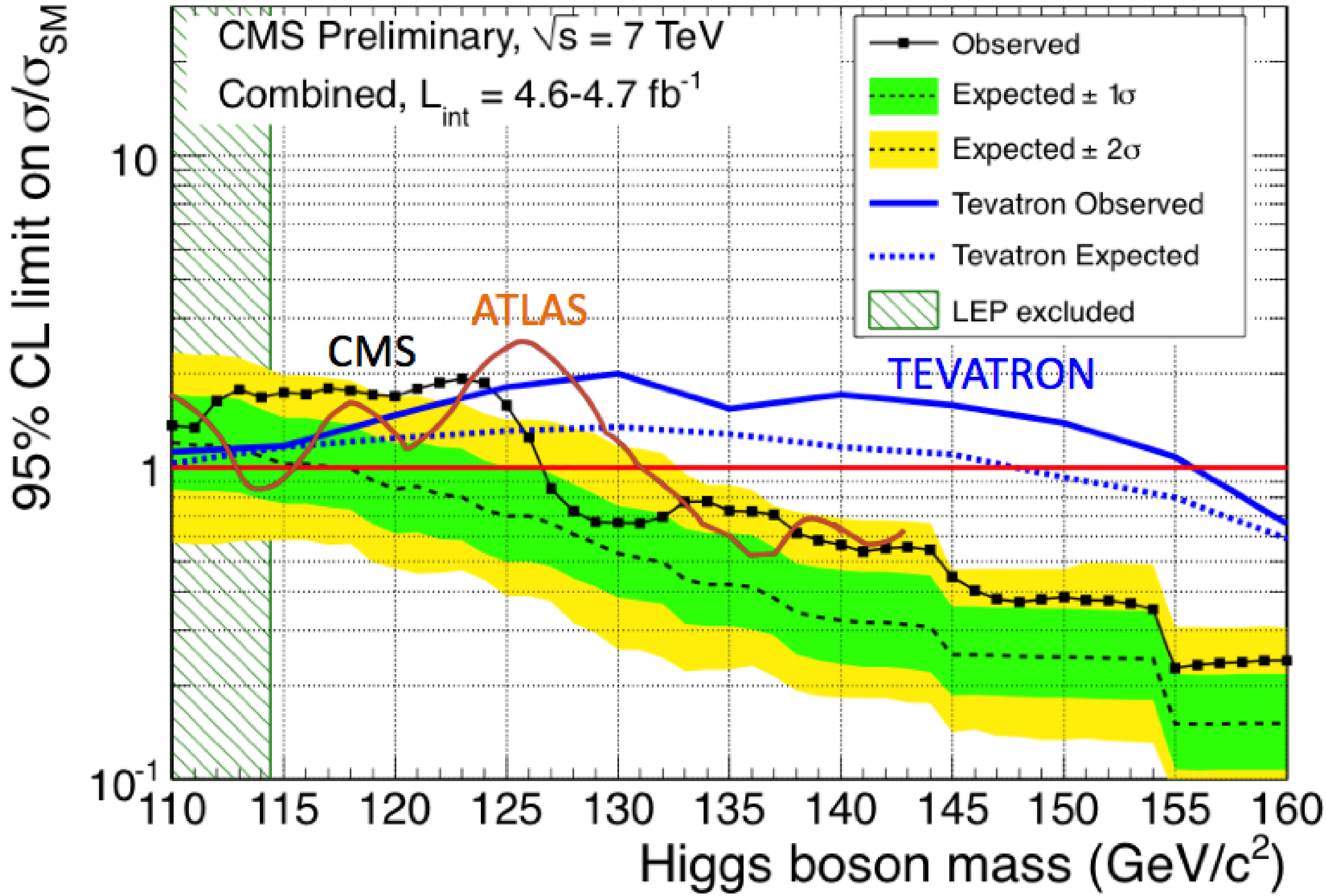
The most obvious "elsewhere" is CMS

Also in CMS there is an excess, but smaller (2.6 σ)



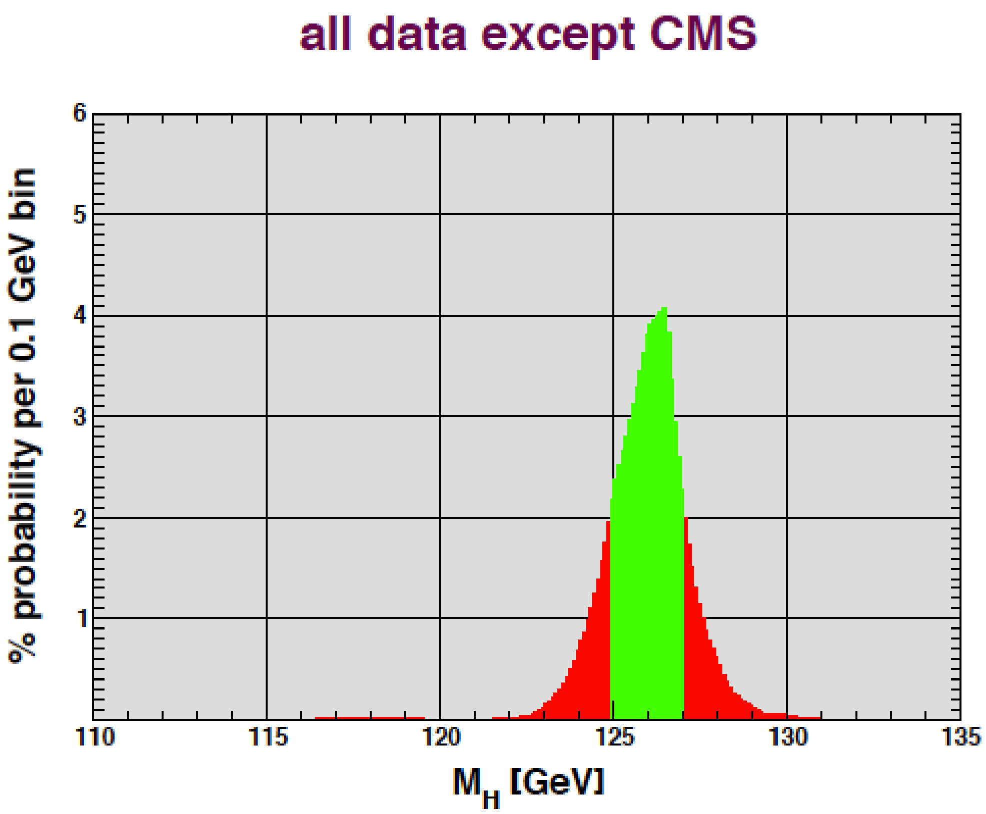
Here is an attempt to put all the evidence together

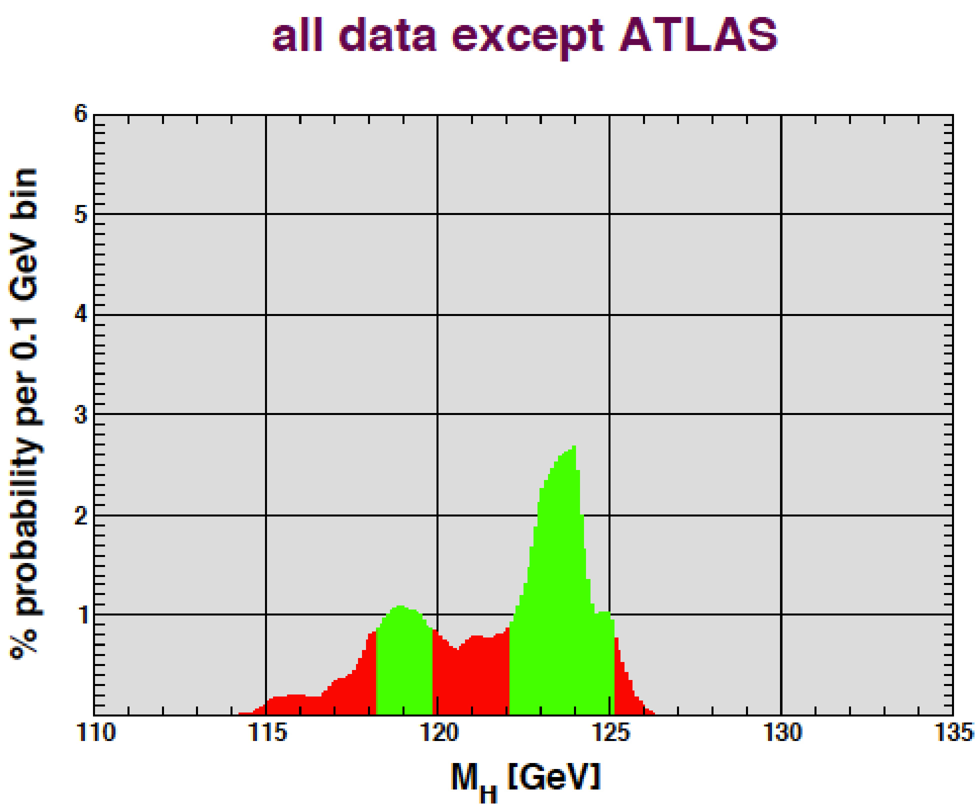
Kilminster
Zurich Jan. '12



Do the masses really coincide?

Erler '11

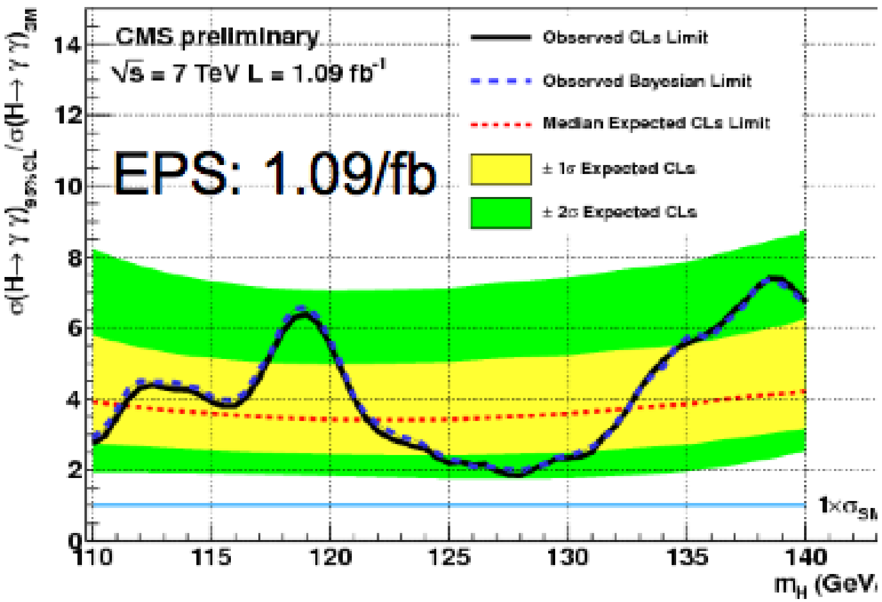


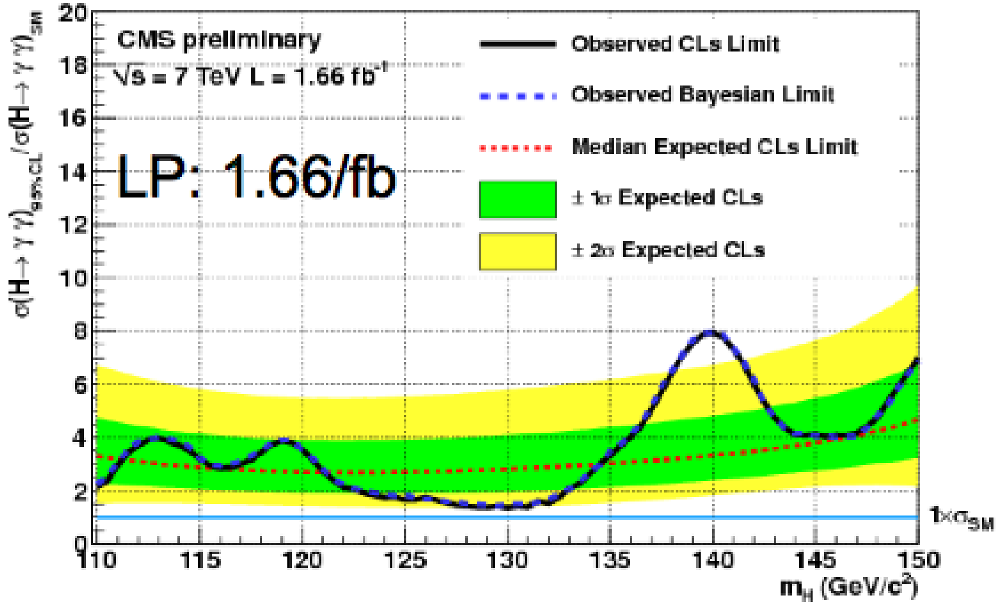


Peaks come and go!

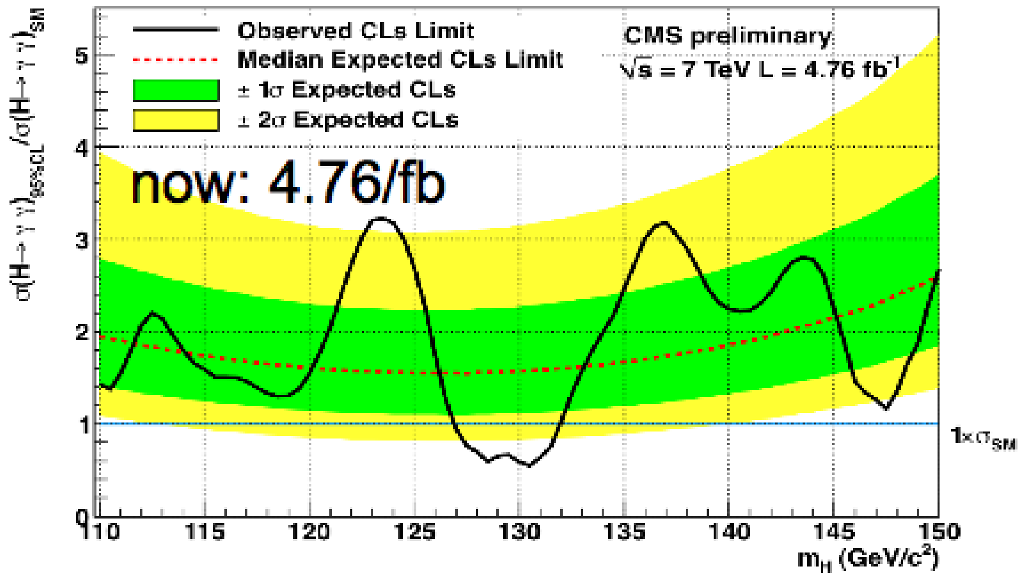
CMS History: $H \to \gamma\gamma$

Paus
Zurich Jan. '12

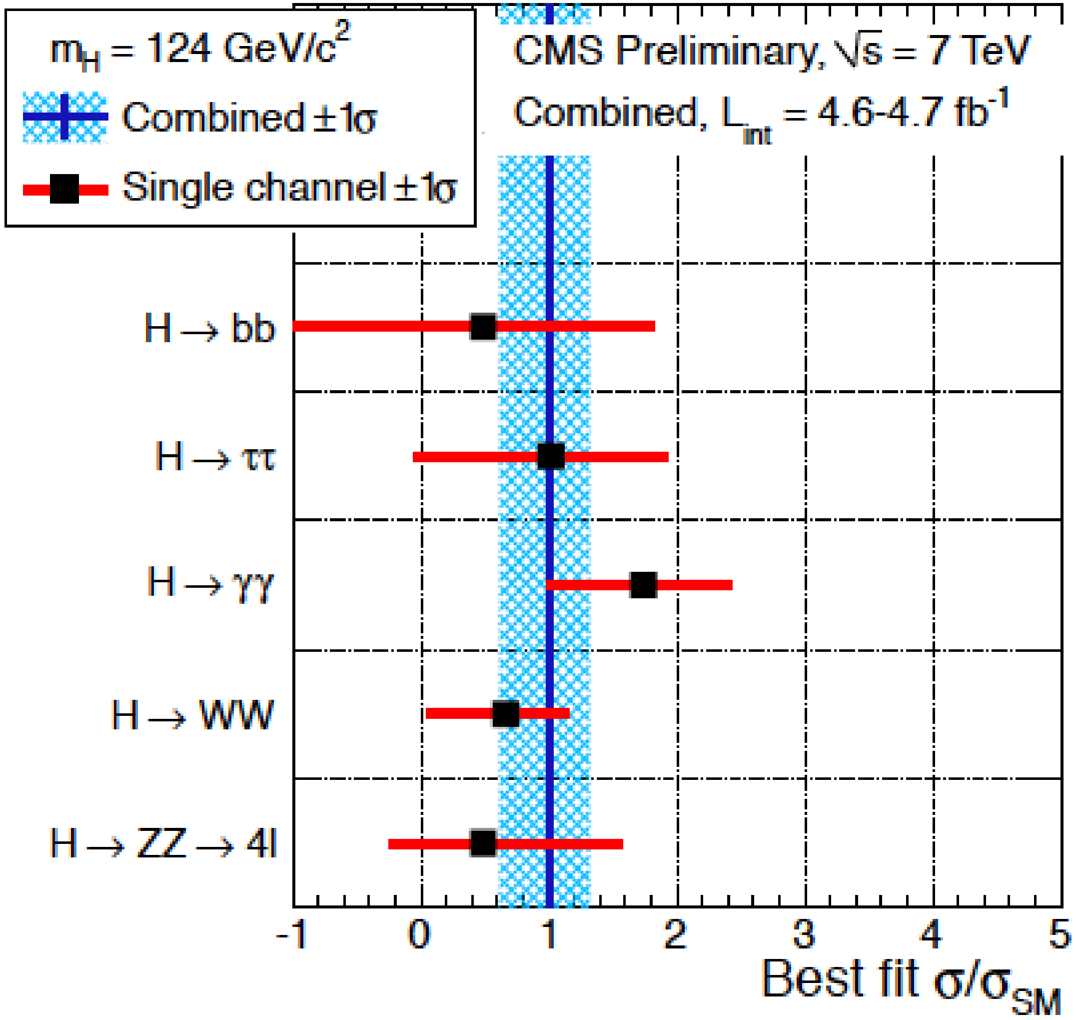




- EPS (1.09/fb) LP (1.66/fb) Dec 19 (4.76/fb)
- 'peaks' come and go
- of course now we are getting into interesting territory



A moderate enhancement of the $\gamma\gamma$ rate may be indicated



The SM Higgs is close to be observed or excluded!

Either the SM Higgs is very light (115.5 - 127 GeV)
or rather heavy (i.e. $>$ 600 GeV)

The range m_H = 115.5 - 127 GeV is in agreement with precision tests, compatible with the SM and also with the SUSY extensions of the SM

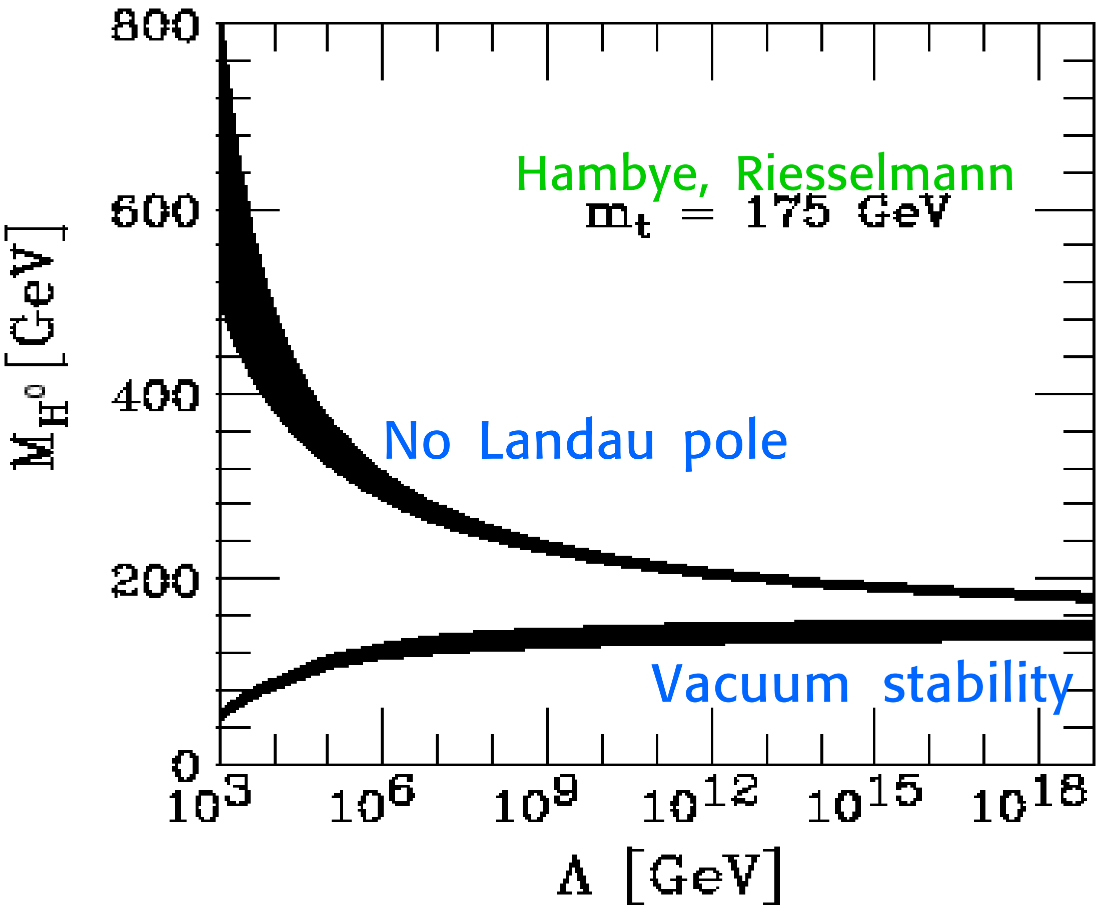
m_H ~125 GeV is what you expect from a direct interpretation of EW precision tests: no fancy conspiracy with new physics to fake a light Higgs while the real one is heavy

m_H $>$ 600 GeV would point to the conspiracy alternative

Theoretical bounds on the SM Higgs mass

Λ: scale of new physics beyond the SM

Upper limit: No Landau pole up to Λ
Lower limit: Vacuum (meta)stability

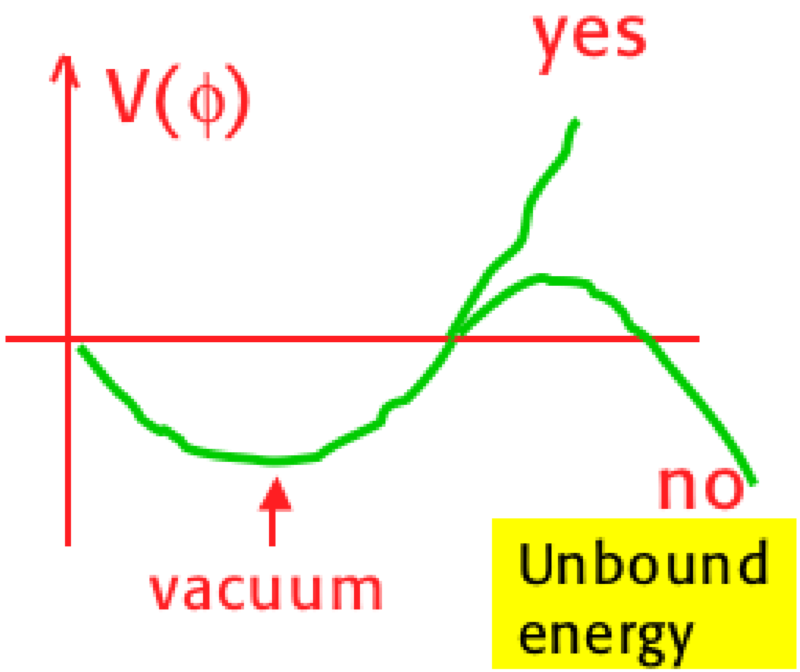


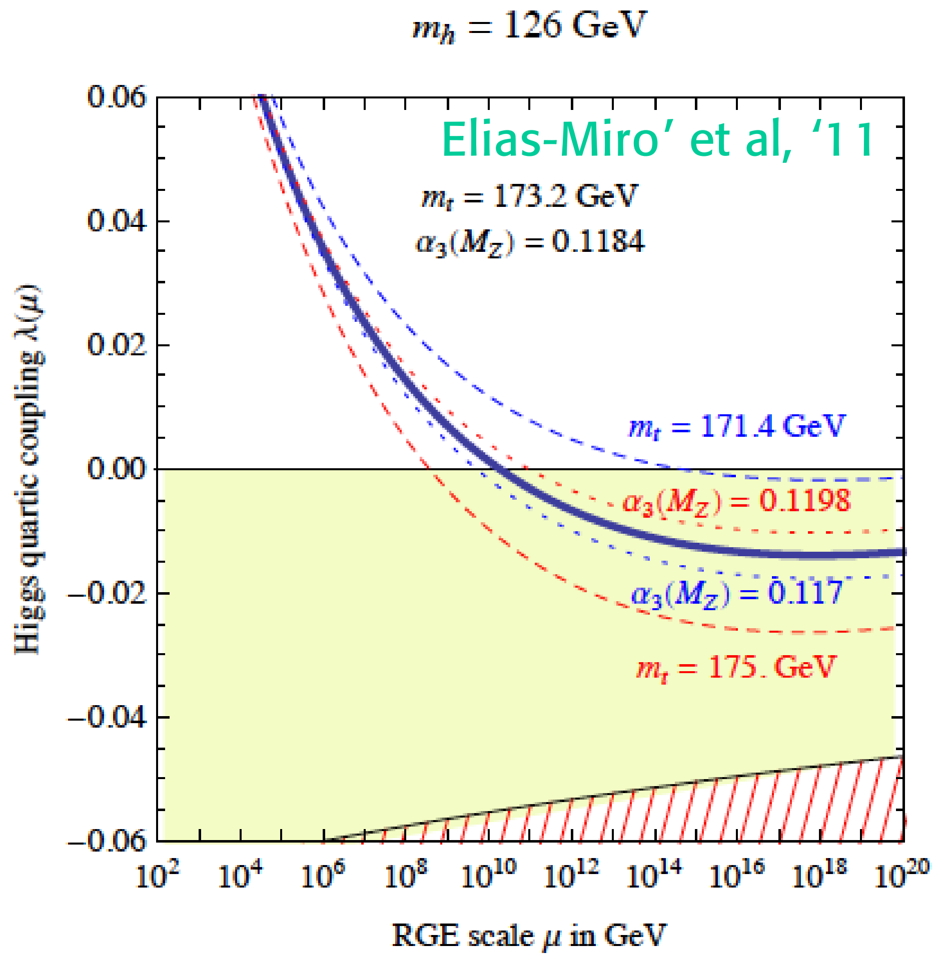
If the SM would be valid up to M_{GUT}, M_{Pl} with a stable vacuum then m_H would be limited in a small range

depends on m_t and α_s → $130\ \text{GeV} < m_H < 180\ \text{GeV}$

But metastability (with sufficiently long lifetime) is enough!

$$V[\phi] = -\mu^2\phi^2 + \lambda\phi^4$$

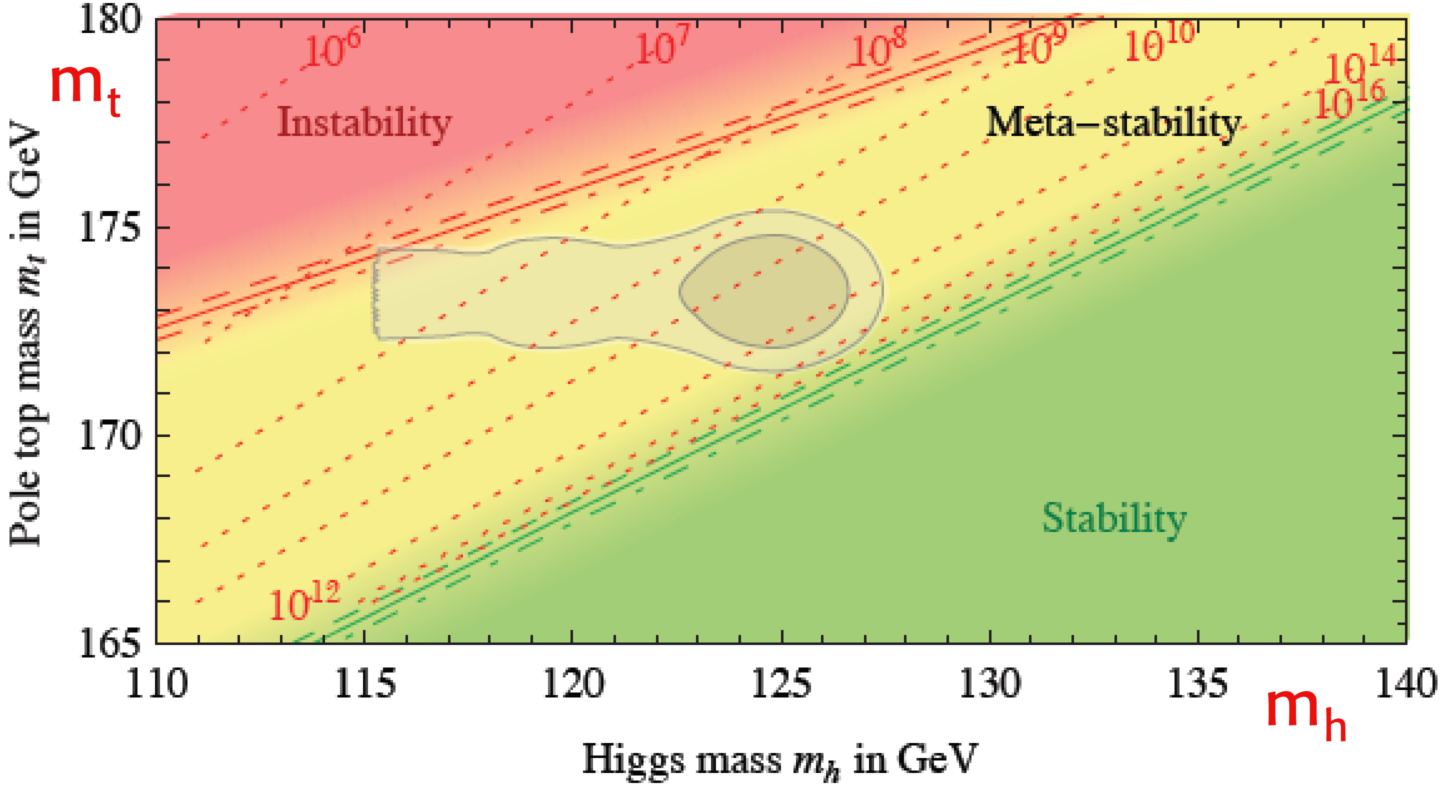




In the absence of new physics, for $m_H \sim 125$ GeV,
the Universe becomes metastable at a scale $\Lambda \sim 10^{10}$ GeV

But the SM remains viable up to M_{Pl} (Early universe implications)

Elias-Miro' et al, '11



Note that $\lambda=0$ at the Planck scale (and no physics in between) implies $m_H \sim 130$ GeV depending on m_t and α_s

$$m_h > 130\,\mathrm{GeV} + 1.8\,\mathrm{GeV}\left(\frac{m_t - 173.2\,\mathrm{GeV}}{0.9\,\mathrm{GeV}}\right) - 0.5\,\mathrm{GeV}\left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right) \pm 3\ \mathrm{GeV}$$

⊕ not far from 125 GeV

Elias-Miro' et al, Holthausen et al, Wetterich '11

The Standard Model works very well

So, why not find the Higgs and declare particle physics solved? Why one expects New Physics?

Because of both:

Conceptual problems

- Quantum gravity
- The hierarchy problem
- The flavour puzzle

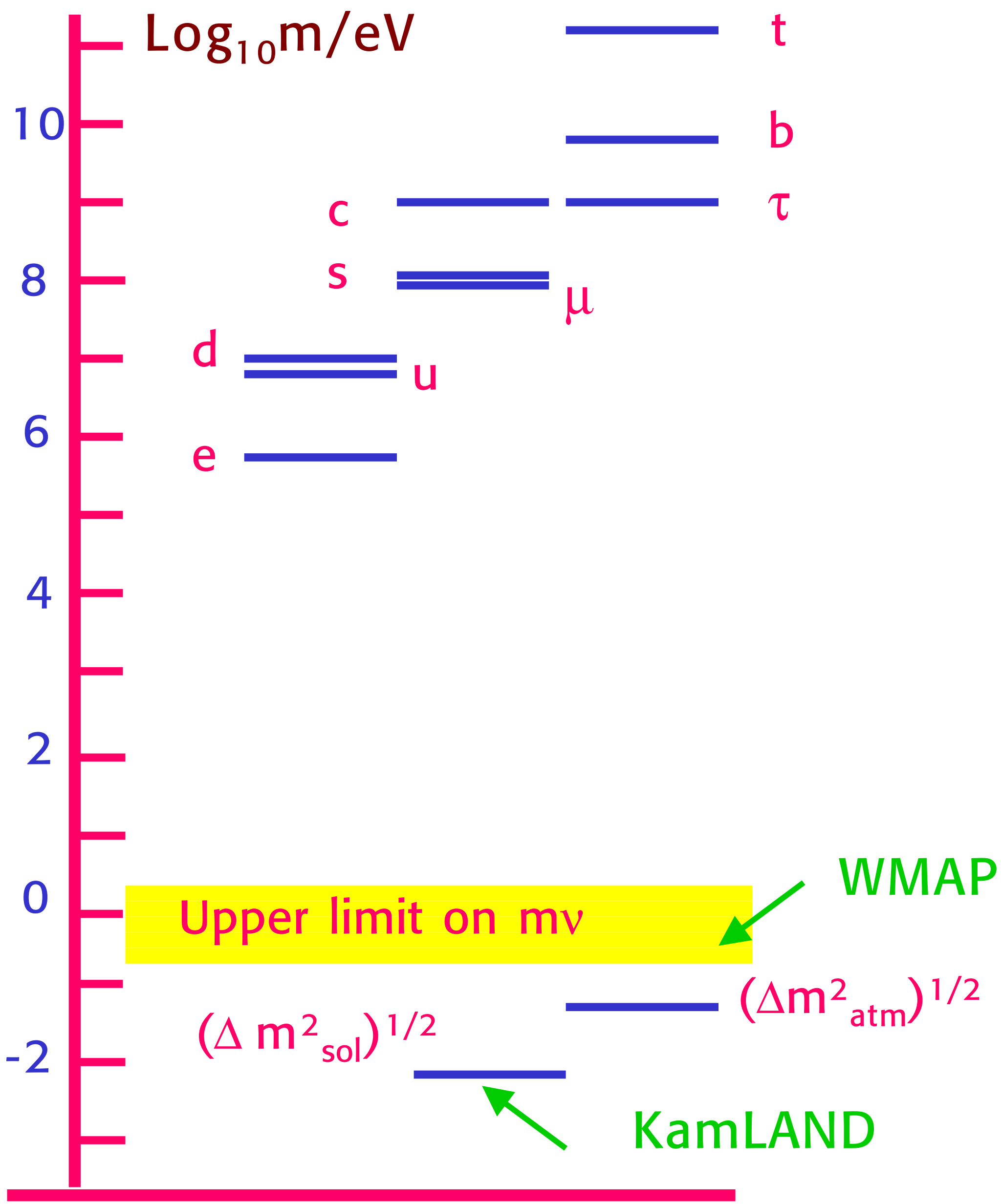
.....

and experimental clues:

- Neutrino masses
- Coupling unification
- Dark matter
- Baryogenesis
- Vacuum energy
- some experimental anomalies: $(g\text{-}2)_\mu$, ...

Some of these problems point at new physics at the weak scale: eg
Hierarchy
Dark matter (perhaps)

insert here your preferred hints



Neutrino masses are really special!

$m_t/(\Delta m^2_{atm})^{1/2} \sim 10^{12}$

Massless ν's?

- no ν_R
- L conserved

Small ν masses?

- ν_R very heavy
- L not conserved

Very likely:
ν's are special as they are Majorana fermions

A very natural and appealing explanation:

ν's are nearly massless because they are Majorana particles and get masses through L non conserving interactions suppressed by a large scale $M \sim M_{GUT}$

$$m_\nu \sim \frac{m^2}{M}$$

$m: \leq m_t \sim v \sim 200$ GeV
M: scale of L non cons.

Note:

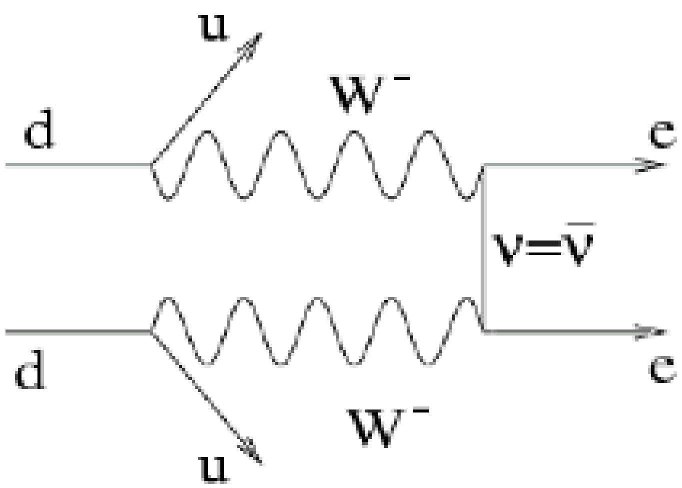
$m_\nu \sim (\Delta m^2_{atm})^{1/2} \sim 0.05$ eV
$m \sim v \sim 200$ GeV

$M \sim 10^{14} - 10^{15}$ GeV

Neutrino masses are a probe of physics at M_{GUT} !

How to prove that ν's are Majorana fermions?

All we know from experiment on ν masses strongly indicates that ν's are Majorana particles and that L is not conserved (but a direct proof still does not exist).



$0\nu\beta\beta$ = dd -> uue^-e^-

Detection of $0\nu\beta\beta$ (neutrinoless double beta decay) would be a proof of L non conservation ($\Delta L=2$).
Thus a big effort is devoted to improving present limits and possibly to find a signal.

- Heidelberg-Moscow, Cuoricino-Cuore, GERDA, •••••

Baryogenesis by decay of heavy Majorana ν's

BG via Leptogenesis near the GUT scale

$T \sim 10^{12\pm3}$ GeV (after inflation)

Buchmuller,Yanagida, Plumacher, Ellis, Lola, Giudice et al, Fujii et al ….

Only survives if $\Delta(B\text{-}L)$ is not zero
(otherwise is washed out at T_{ew} by instantons)

Main candidate: decay of lightest ν_R ($M \sim 10^{12}$ GeV)

L non conserv. in ν_R out-of-equilibrium decay:
B-L excess survives at T_{ew} and gives the obs. B asymmetry.

Quantitative studies confirm that the range of m_i from ν oscill's is compatible with BG via (thermal) LG

In particular the bound was derived for hierarchy

$m_i < 10^{-1}$ eV

Buchmuller, Di Bari, Plumacher; Giudice et al; Pilaftsis et al; Hambye et al

Can be relaxed for degenerate neutrinos
So fully compatible with oscill'n data!!

Dark Matter

WMAP, SDSS, 2dFGRS….

Most of the Universe is not made up of atoms: $\Omega_{tot} \sim 1$, $\Omega_b \sim 0.045$, $\Omega_m \sim 0.27$

Most is Dark Matter and Dark Energy

Most Dark Matter is Cold (non relativistic at freeze out)
Significant Hot Dark matter is disfavoured
Neutrinos are not much cosmo-relevant: $\Omega_\nu < 0.015$

SUSY has excellent DM candidates: eg Neutralinos (--> LHC)
Also Axions are still viable (introduced to solve strong CPV)
(in a mass window around m $\sim 10^{-4}$ eV and $f_a \sim 10^{11}$ GeV
but these values are simply a-posteriori)

Identification of Dark Matter is a task of enormous importance for particle physics and cosmology

LHC?

LHC has good chances because it can reach any kind of WIMP:

WIMP: Weakly Interacting Massive Particle
with m ~ 10^1-10^3 GeV

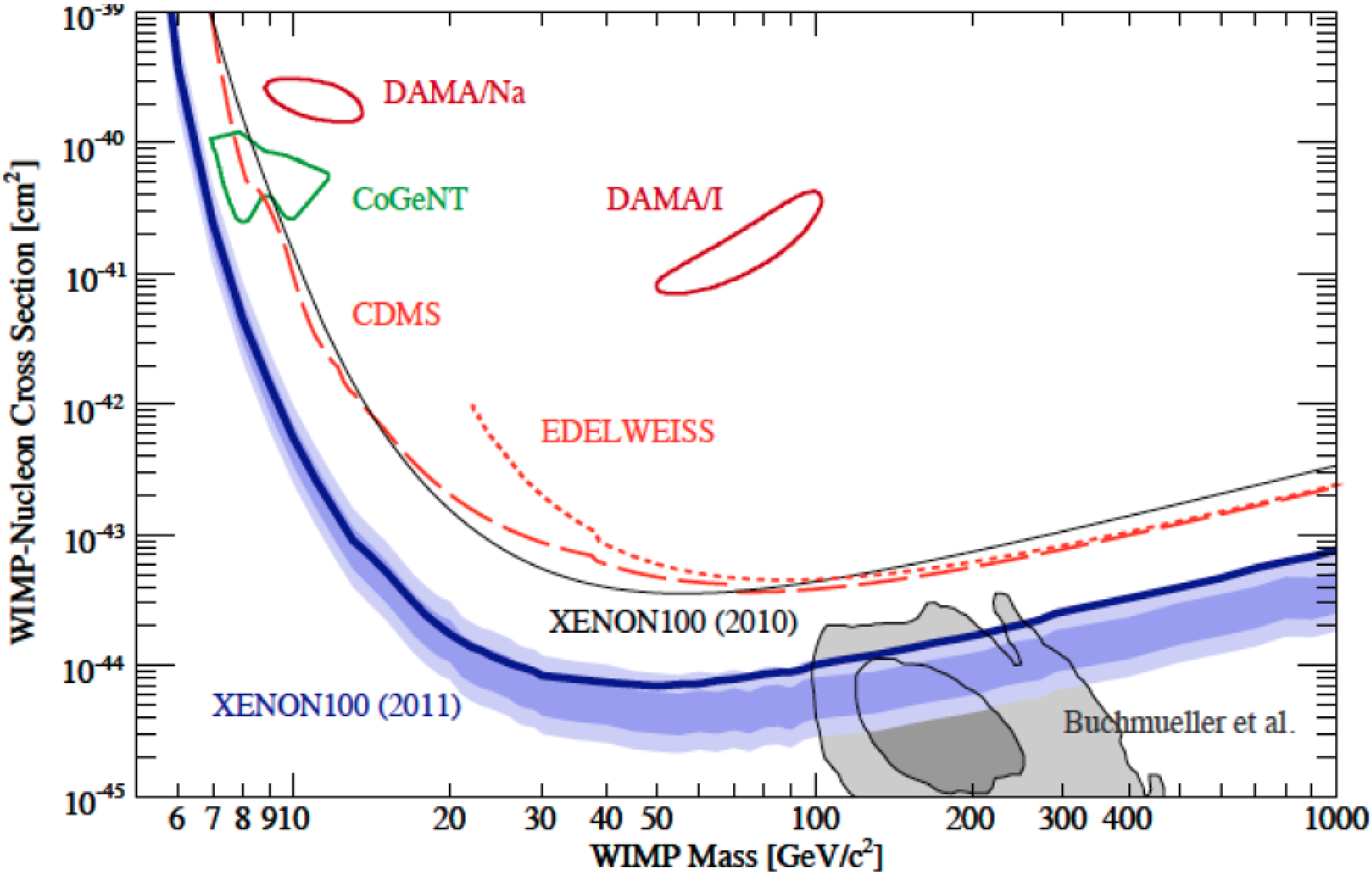
For WIMP's in thermal equilibrium after inflation the density is:

$$\Omega_\chi h^2 \simeq const. \cdot \frac{T_0^3}{M_{\rm Pl}^3 \langle \sigma_A v \rangle} \simeq \frac{0.1 \text{ pb} \cdot c}{\langle \sigma_A v \rangle}$$

can work for typical weak cross-sections!!!

This "coincidence" is a good indication in favour of a WIMP explanation of Dark Matter

Strong competition from underground labs



A crucial question for the LHC

Is Dark Matter a WIMP?

LHC will probably tell yes or no to WIMPS

Conceptual problems of the SM

Most clearly:

- No quantum gravity (M_{Pl} ~ 10^{19} GeV)
- But a direct extrapolation of the SM leads directly to GUT's (M_{GUT} ~ 10^{16} GeV)

M_{GUT} close to M_{Pl}

- suggests unification with gravity as in superstring theories
- poses the problem of the relation m_W vs M_{GUT}- M_{Pl}

Can the SM be valid up to M_{GUT}- M_{Pl}?? ← The "big" hierarchy problem

Not only it looks very unlikely, but the new physics must be near the weak scale!

With new physics at Λ the SM is only an effective theory.

After integration of the heavy d.o.f. :

$\mathcal{L}_i$: operator of dim i

$$\mathcal{L} = o(\Lambda^2)\mathcal{L}_2 + o(\Lambda)\mathcal{L}_3 + o(1)\mathcal{L}_4 \quad + o(1/\Lambda)\mathcal{L}_5 + o(1/\Lambda^2)\mathcal{L}_6 + \dots$$

Renorm.ble part — Non renorm.ble part

In absence of special symmetries or selection rules,
by dimensions $c_i\mathcal{L}_i \sim o(\Lambda^{4-i})\mathcal{L}_i$

$\mathcal{L}_2$: Boson masses ϕ^2. In the SM the mass in the Higgs potential is unprotected: $c_2 \sim o(\Lambda^2)$ $m_{W,H}$ should be $o(\Lambda)$!!

$\mathcal{L}_3$: Fermion masses $\bar{\psi}\psi$. Protected by chiral symmetry and SU(2)xU(1): $\Lambda \to m\log\Lambda$

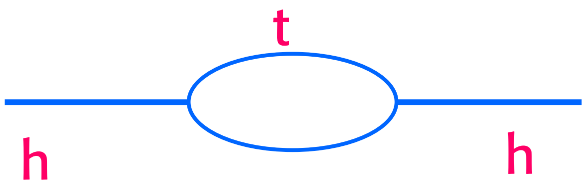
$\mathcal{L}_4$: Renorm.ble interactions, e.g. $\bar{\psi}\gamma^\mu\psi A_\mu$

$\mathcal{L}_{i>4}$: Non renorm.ble: suppressed by $1/\Lambda^{i-4}$ e.g. $1/\Lambda^2\bar{\psi}\gamma^\mu\psi\bar{\psi}\gamma^\mu\psi$

The "little hierarchy" problem

e.g. the top loop (the most pressing):

$m_h^2 = m^2_{bare} + \delta m_h^2$



$$\delta m^2_{h|top} = -\frac{3G_F}{2\sqrt{2}\pi^2} m_t^2 \Lambda^2 \sim -(0.2\Lambda)^2$$

$\Lambda \sim o(1\text{TeV})$

This hierarchy problem demands new physics near the weak scale

Λ: scale of new physics beyond the SM

- $\Lambda >> m_Z$: the SM is so good at LEP
- $\Lambda \sim$ few times $G_F^{-1/2} \sim o(1\text{TeV})$ for a natural explanation of m_h or m_W

Barbieri, Strumia

The LEP Paradox: m_h light, new physics must be close but its effects were not visible at LEP2

The B-factory Paradox: and not visible in flavour physics

Precision Flavour Physics

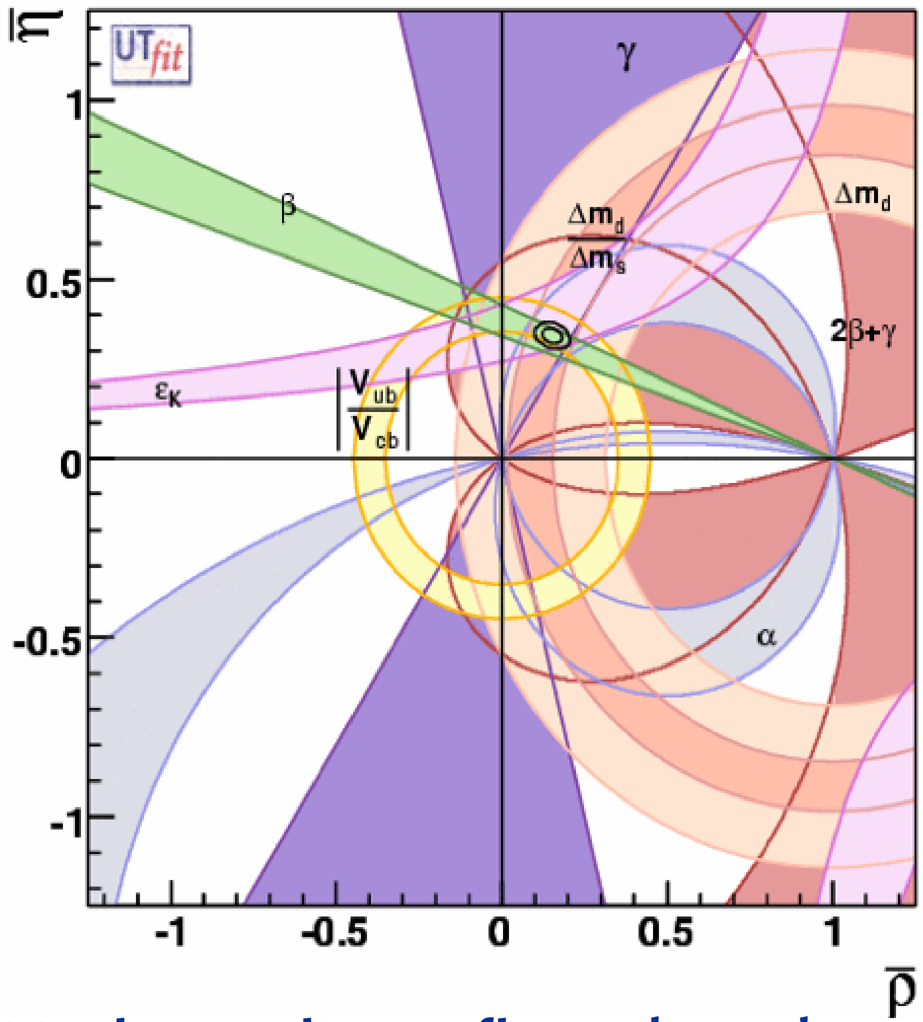
Another area where the SM is good, too good.....

With new physics at ~ TeV one would expect
the SM suppression of FCNC and the CKM
mechanism for CP violation to be sizably modified.

But this is not the case

an intriguing mystery and a major challenge for models of
new physics

No clear signs of new physics in B decays (BaBar, Belle,Tevatron)



And now the LHCb experiment at the LHC has gone further in this direction

The CKM picture is confirmed as the main source of CPV in the quark sector

⊕ This poses strong constraints for models BSM

Adding effective operators to SM generally leads to very large Λ

$$M(B_d\text{-}\bar{B}_d) \sim \frac{(y_t V_{tb}{}^* V_{td})^2}{16\,\pi^2 M_W{}^2} + c_{NP}\frac{1}{\Lambda^2}$$

Isidori

c_{NP}:

- ~ 1 $\xrightarrow{\text{tree/strong + generic flavour}}$ $\Lambda \gtrsim 2\times10^4$ TeV [K]
- $\sim 1/(16\,\pi^2)$ $\xrightarrow{\text{loop + generic flavour}}$ $\Lambda \gtrsim 2\times10^3$ TeV [K]
- $\sim (y_t V_{ti}{}^* V_{tj})^2$ $\xrightarrow{\text{tree/strong + MFV}}$ $\Lambda \gtrsim 5$ TeV [K & B]
- $\sim (y_t V_{ti}{}^* V_{tj})^2/(16\,\pi^2)$ $\xrightarrow{\text{loop + MFV}}$ $\Lambda \gtrsim 0.5$ TeV [K & B]

But the hierarchy problem demands Λ in the few TeV range

only assuming $c_{NP} \sim (y_t V_{tb}{}^* V_{td})^2$ (or anyway small)

we get a bound on Λ in the TeV range

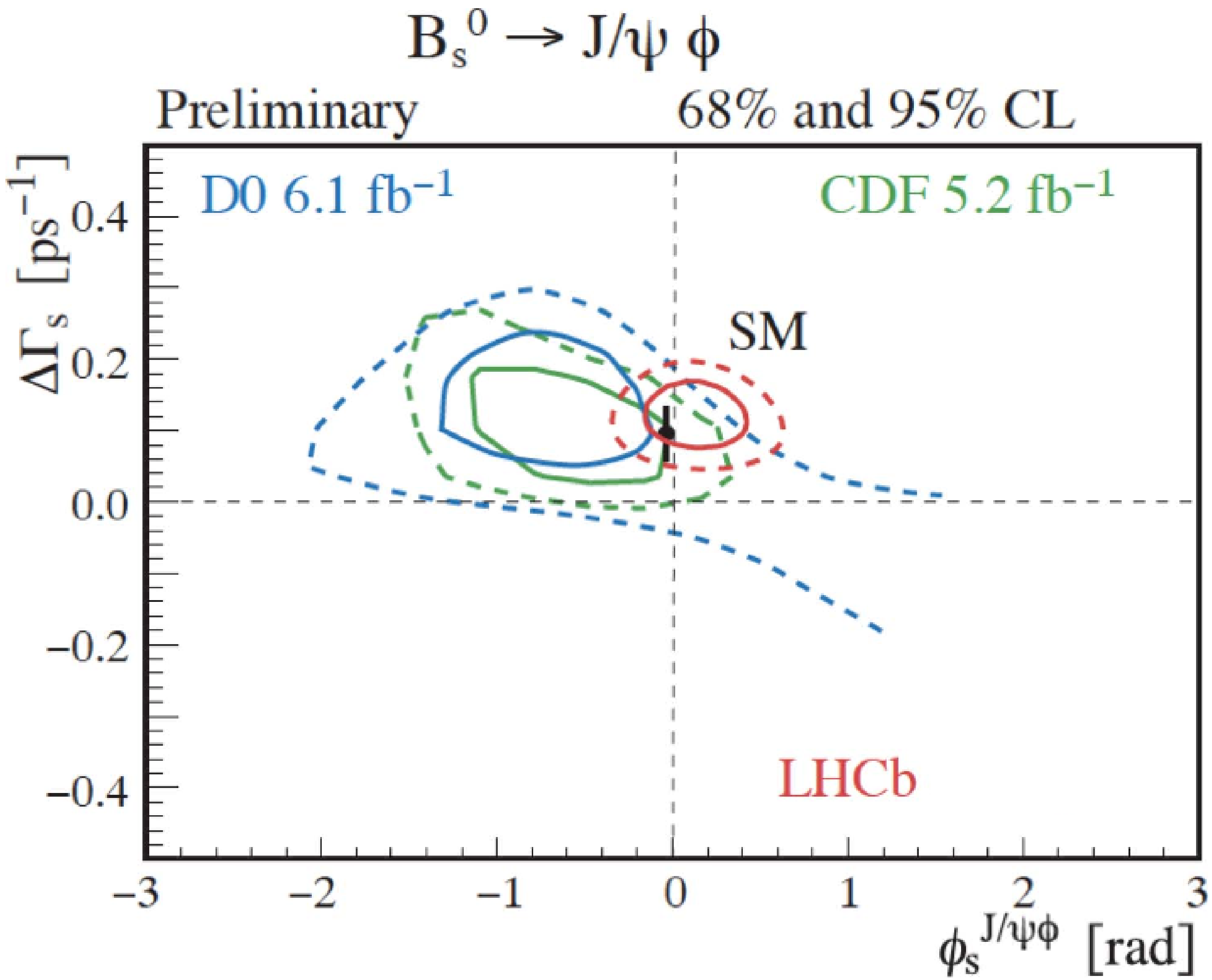
eg in Minimal Flavour Violation (MFV) models

D'Ambrosio, Giudice, Isidori, Strumia'02

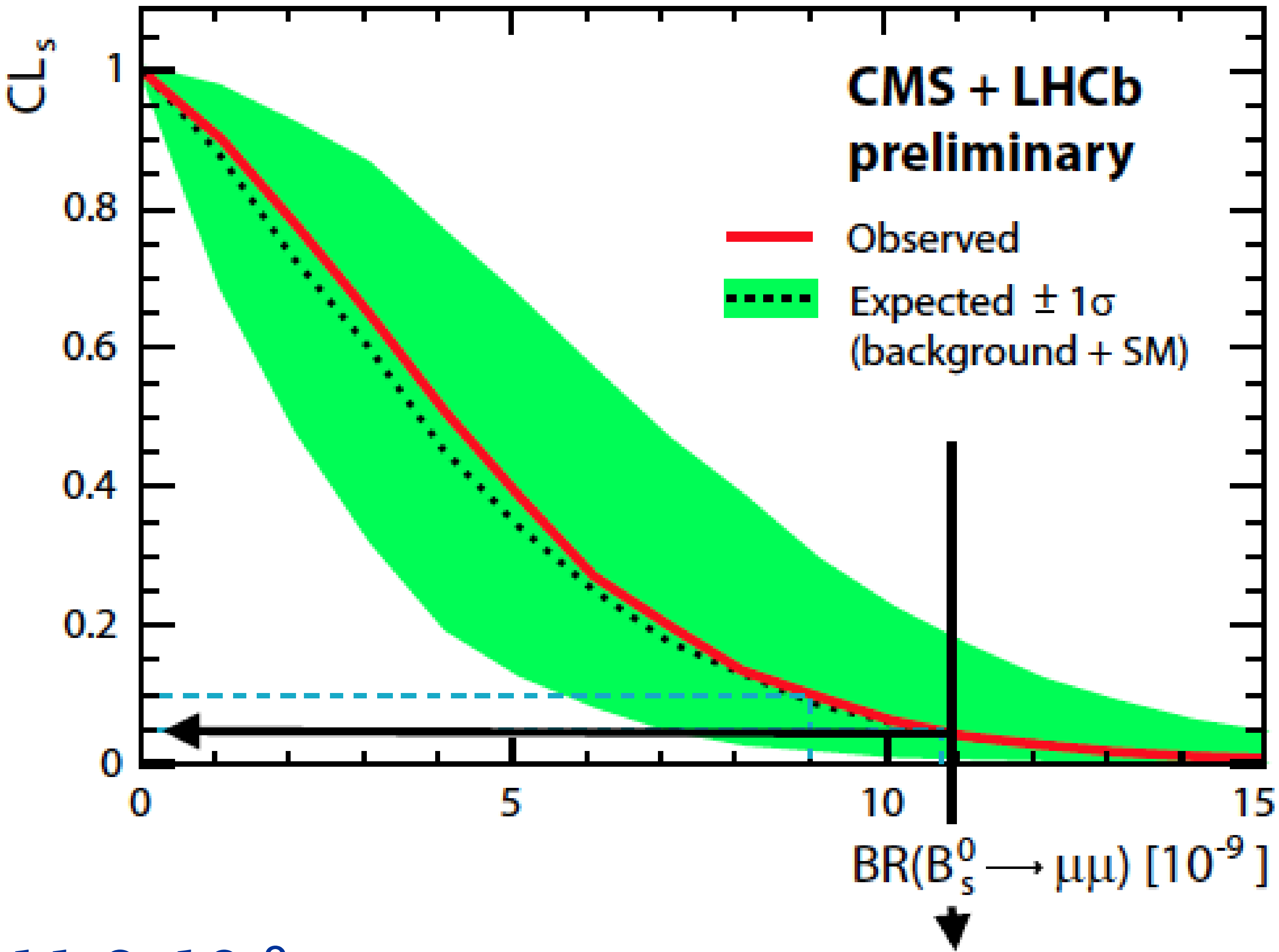
LHC and flavour physics

Important results from LHCb

Back into agreement with SM



CMS & LHCb combined (presented at EPS'11 Grenoble)



< 11×10^{-9} @ 95% CL

cfr
CDF 18+11-9 10^{-9}
SM 3.2±0.2 10^{-9}

A crucial question for the LHC

What damps the top loop Λ^2 dependence?

- the s-top (SUSY)
- some new fermion

  t′ (Little Higgs)

  KK recurrences of the top (Extra dim.)

  ......

- nothing dumps it and we accept the ever increasing fine tuning

Solutions to the hierarchy problem

- Supersymmetry: boson-fermion symm.

  The most ambitious and widely accepted
  Simplest versions now marginal
  Plenty of viable alternatives

- Strong EWSB: Technicolor

  Strongly disfavoured by LEP. Coming back in new forms

  Composite Higgs

  Higgs as PG Boson, Little Higgs models……

- Extra spacetime dim's that somehow "bring" M_{Pl} down to o(1TeV) [large ED, warped ED, ……]. Holographic composite H

  Exciting. Many facets. Rich potentiality. No baseline model emerged so far

- Ignore the problem: invoke the anthropic principle

  Extreme, but not excluded by the data

The anthropic route

The scale of the cosmological constant is a big mystery.

$\Omega_\Lambda \sim 0.75$ → $\rho_\Lambda \sim (2\ 10^{-3}\ \mathrm{eV})^4 \sim (0.1\mathrm{mm})^{-4}$ → Similar to m_ν!?

In Quantum Field Theory: $\rho_\Lambda \sim (\Lambda_{cutoff})^4$

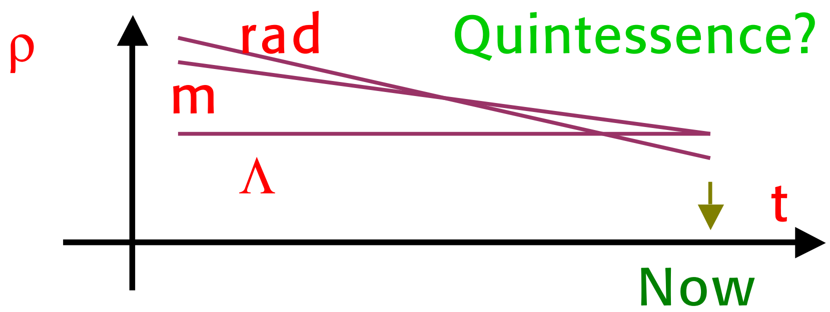
If $\Lambda_{cutoff} \sim M_{Pl}$ → $\rho_\Lambda \sim 10^{123}\,\rho_{obs}$

Exact SUSY would solve the problem: $\rho_\Lambda = 0$

But SUSY is broken: $\rho_\Lambda \sim (\Lambda_{SUSY})^4 \sim 10^{59}\,\rho_{obs}$

It is interesting that the correct order is $(\rho_\Lambda)^{1/4} \sim (\Lambda_{EW})^2/M_{Pl}$

Other problem:
"Why now"?



"Quintessence"
Λ as a vev of a field ϕ?

Coupled to gauge singlet matter, eg ν_R, to solve magnitude and why now?

Is naturalness relevant? The multiverse alternative

Speculative physics reasons lead to doubts:

- The empirical value of the cosmological constant Λ poses a tremendous, unsolved naturalness problem

  yet the value of Λ is close to the Weinberg upper bound for galaxy formation

- Possibly our Universe is just one of infinitely many continuously created from the vacuum by quantum fluctuations

- Different physics in different Universes according to the multitude of string theory solutions ($\sim 10^{500}$)

Perhaps we live in a very unlikely Universe but one that allows our existence

Given the stubborn refuse of the SM to step aside, and the terrible unexplained naturalness problem of the cosmological constant, many people have turned to the anthropic philosophy also for the SM

I find applying the anthropic principle to the SM hierarchy problem still completely unmotivated

After all, we can find plenty of models that reduce the fine tuning from 10^{14} to 10^{2}:
so why make our Universe so terribly unlikely?

The case of the cosmological constant is a lot different:
the context is not as fully specified as the for the SM
(quantum gravity, string cosmology, branes in extra dims., wormholes thru different Universes....)

An example of anthropic picture

An enlarged SM (to include RH ν's and no new physics) remains as an open but enormously fine tuned option

A light Higgs

SO(10) non SUSY GUT

SO(10) breaking down to $SU(4)xSU(2)_L xSU(2)_R$ at an intermediate scale (10^{11-12})

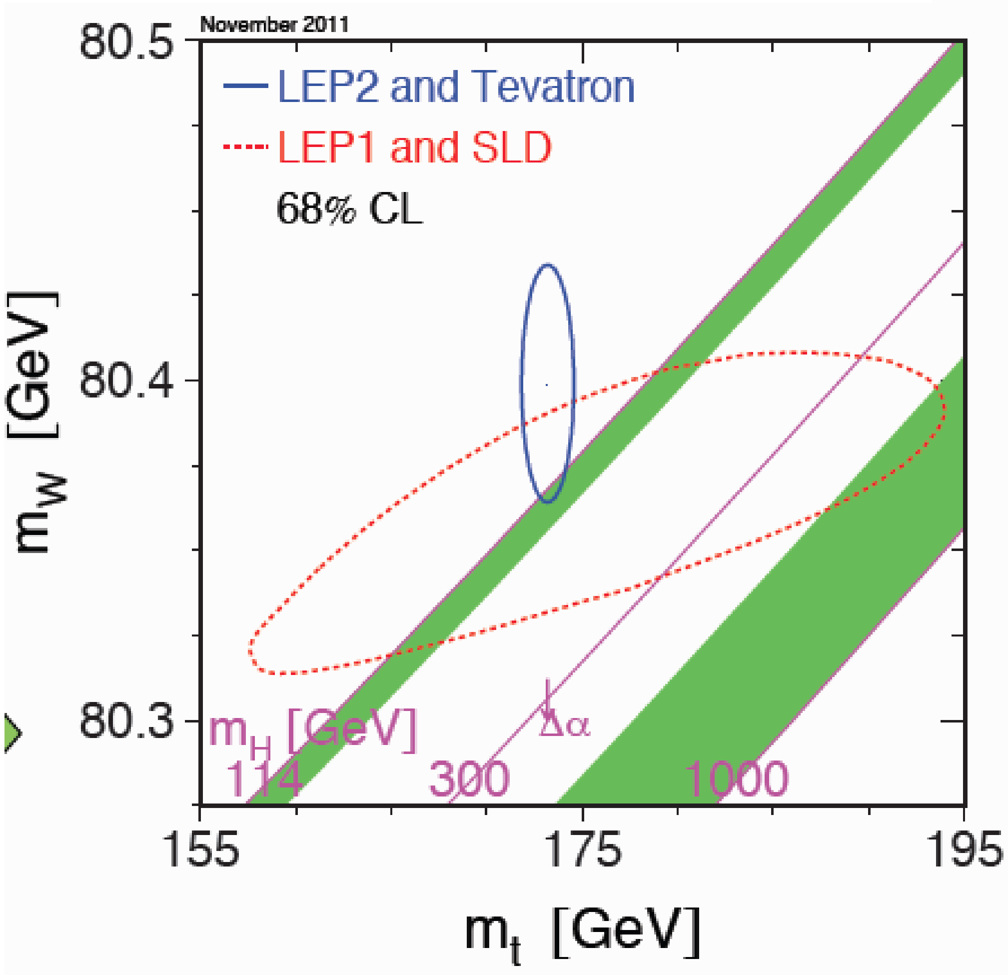
Majorana neutrinos and see-saw (-> $0\nu\beta\beta$)

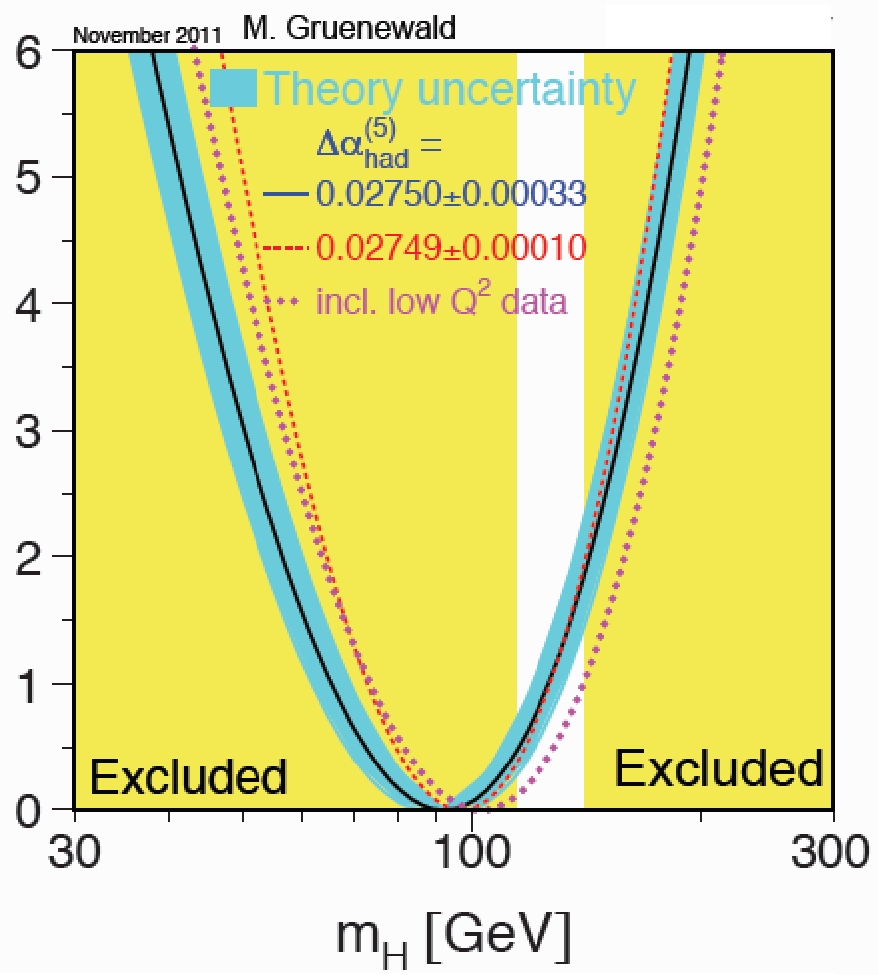
Axions as dark matter

Baryogenesis thru leptogenesis

But: $(g-2)_\mu$ and other present hints of deviations from SM should disappear or be explained away

Some amount of new physics could bring EW precision tests better into focus





The best fit m_H is low, more so if not for A_{FB}^b, m_W is a bit large

Muon g-2

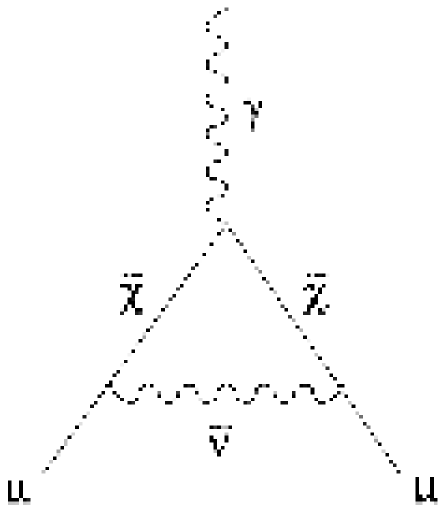
a_μ is a plausible location for a new physics signal!!

eg could be light SUSY (now tension with LHC)

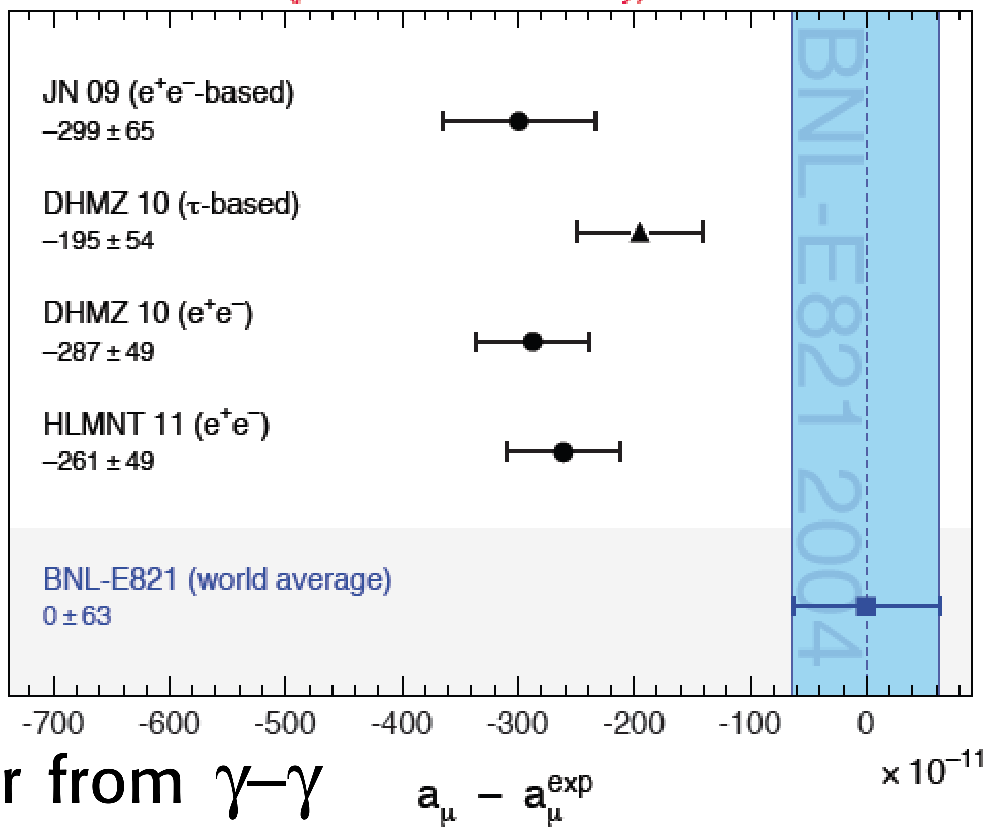
$$a_\mu^{\,exp} - a_\mu^{\,SM} = (28.7 \pm 8.0) \times 10^{-10}$$

- 3.6 "standard deviations" (e^+e^-)
- 2.4 "standard deviations" (τ)

$$\delta a_\mu = 13 \cdot 10^{-10} \left(\frac{100\,GeV}{M_{SUSY}}\right)^2 tg\beta$$



Status: summer 2011 (*published results shown only*)



- Error dominated by th error from γ–γ

Some NP hints from accelerator experiments

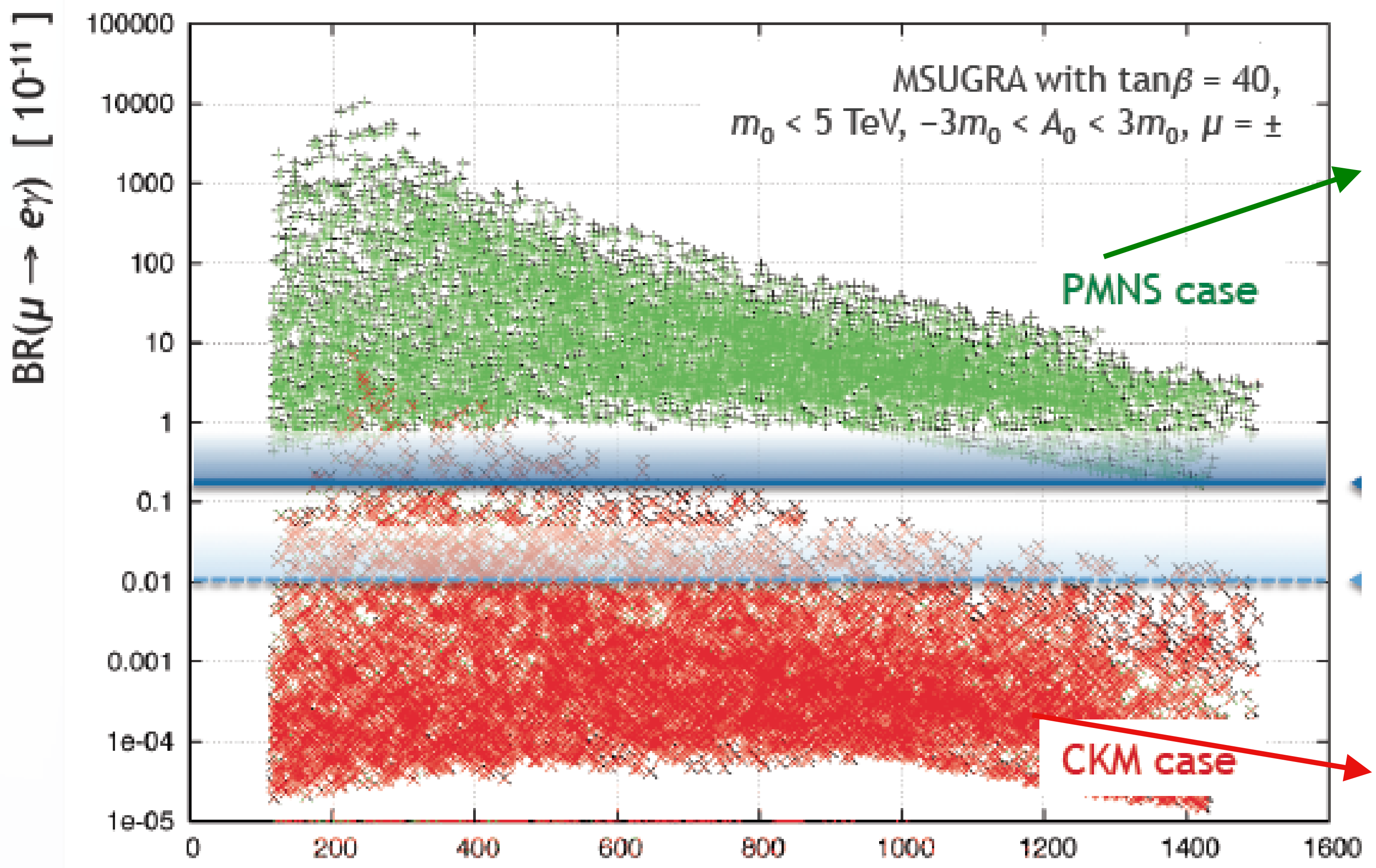
A^b_{FB}	LEP	$\sim 3\sigma$
$(g-2)_\mu$	Brookhaven	$\sim 3\sigma$
tt^{bar} FB asymmetry	Tevatron (mostly CDF)	$\sim 3\sigma$ at large M_{tt}
Dimuon charge asymmetry	D0	$\sim 3.9\sigma$
Wjj excess at $M_{jj} \sim$ 144 GeV only candidate to open prod. of NP	CDF	$\sim 3.2\sigma$ not confirmed by D0, LHC
$B_s \to J/\psi\phi$	Tevatron, LHCb	~went away
$B \to \tau\nu$	BaBar, Belle	$\sim 2.5\sigma$
CPV in $D \to \pi\pi$, KK	LHCb	

....

All of them could still go away!

A non-LHC very important result

MEG new limit on Br(μ -> e γ) < 2.4 10^{-12}



Large mixing in ν Yukawa

MEG now

MEG goal

Small mixing in ν Yukawa

Also goes in the direction of the SM

No neutron electric dipole moment

d_n violates P and T

$\vec{d}_n = d\vec{\sigma}$ $\vec{m}_n = \mu\vec{\sigma}$

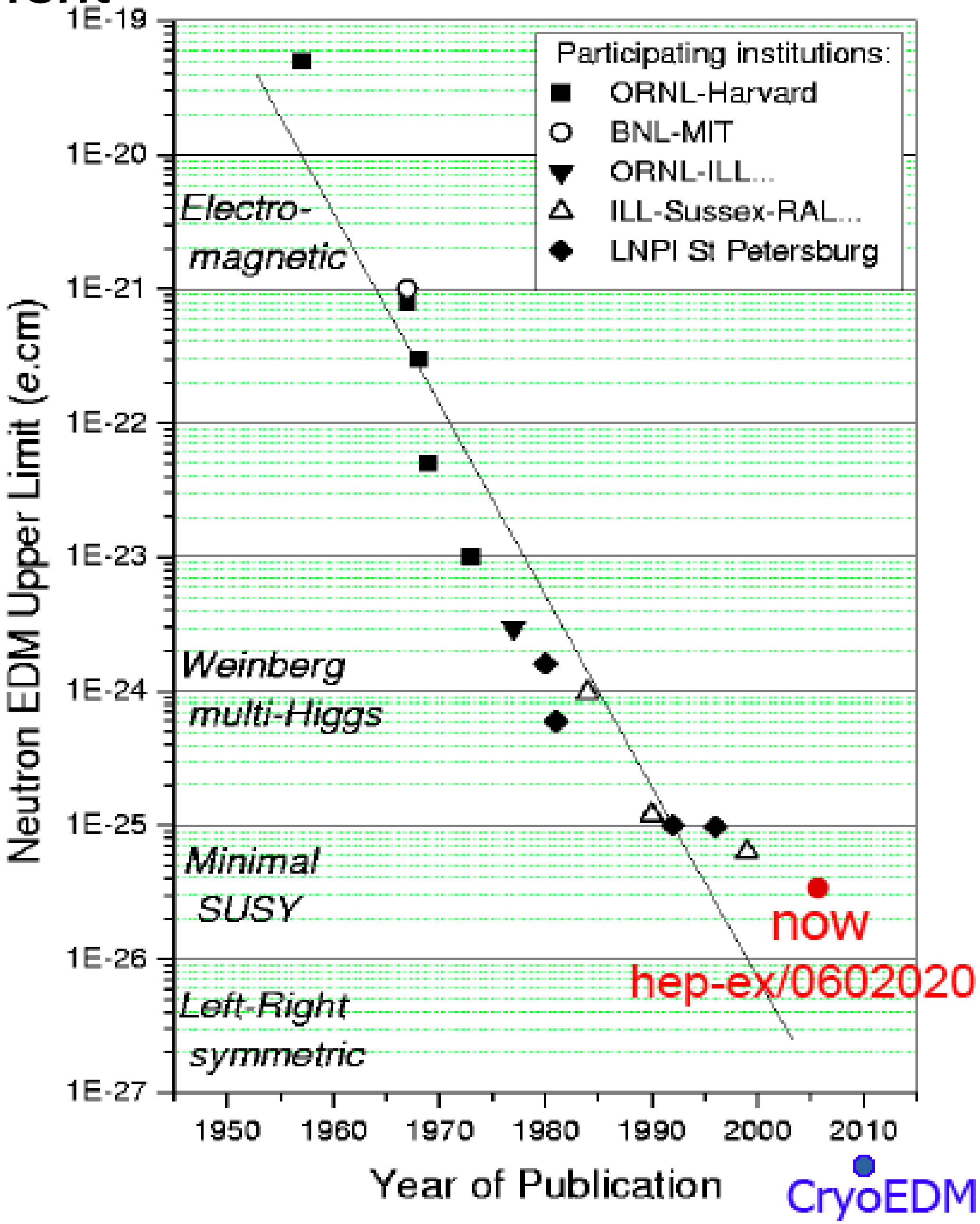
$H \sim -(\vec{d}_n \cdot \vec{E} + \vec{m}_n \cdot \vec{B}) = -(d\vec{E} + \mu\vec{B}) \cdot \vec{\sigma}$

E and B have opposite behaviour under P and T

CPT is conserved, so T violation implies CP violation

Present limit on d_n from Grenoble

$|d_n| < 3\ 10^{-26}$ e cm (90%cl)



A striking result of the 2011 LHC run (> 1 fb^{-1}) is that the new physics is pushed further away

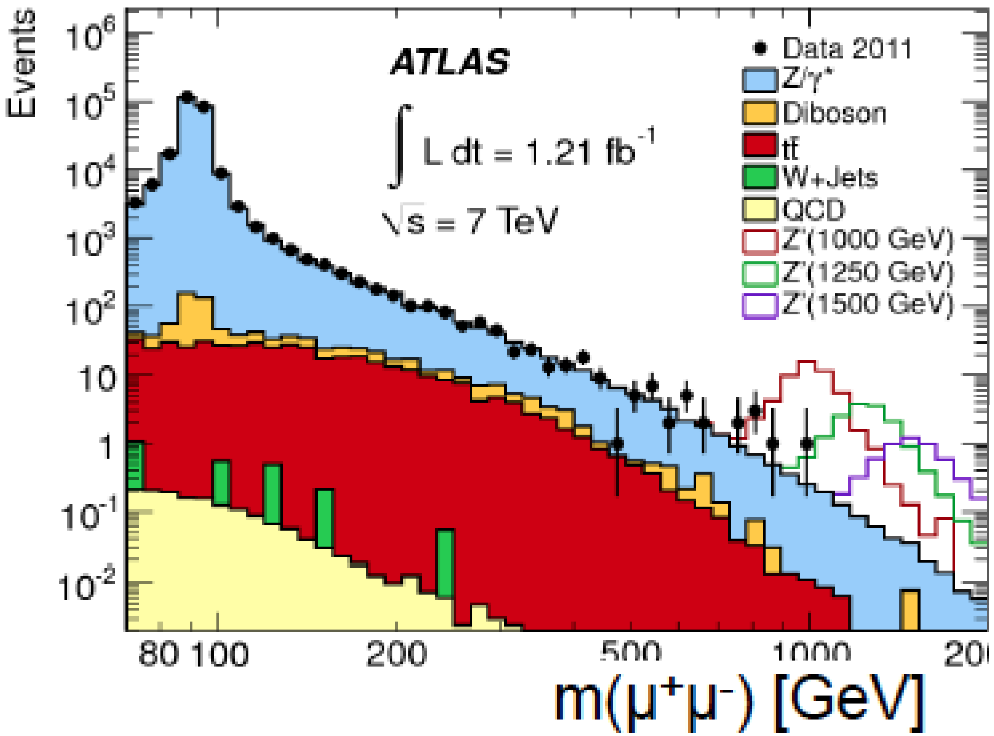
But only ~ 20-25% of the 2011 statistics has been analysed

Examples:

sequential W': $m_{W'} > 2.3$ TeV
sequential Z': $m_{Z'} > 1.9$ TeV
axi-gluon: 2.5-3.2 TeV
gluino: $m_g >$ ~ 0.5 - 1 TeV

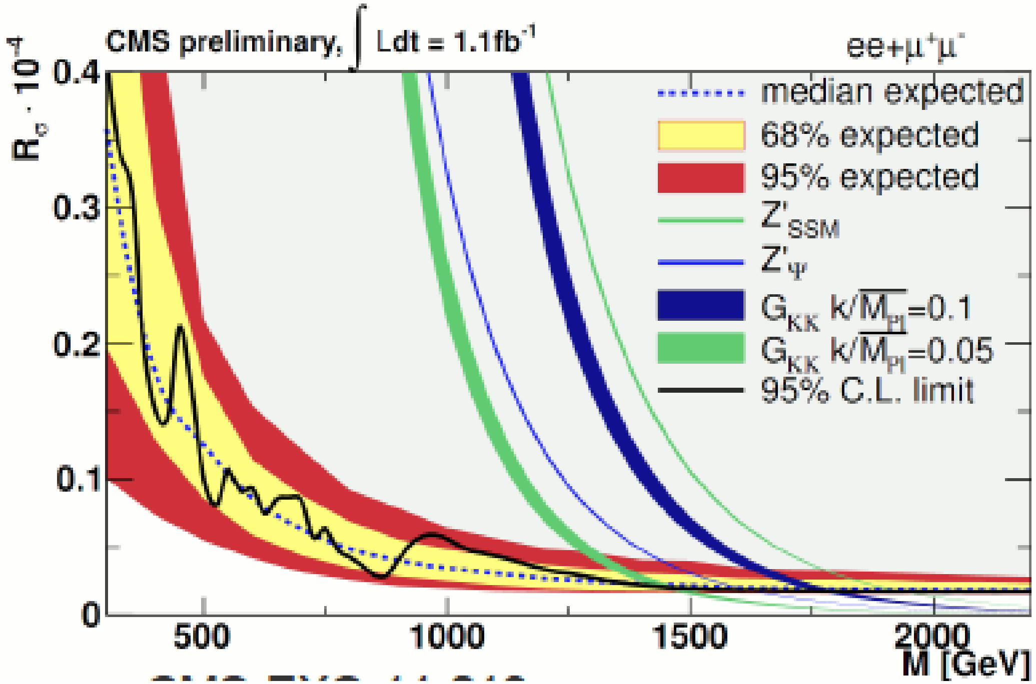
Many generic signatures searched.
Not a single significant hint of new physics found

Di-lepton Channel



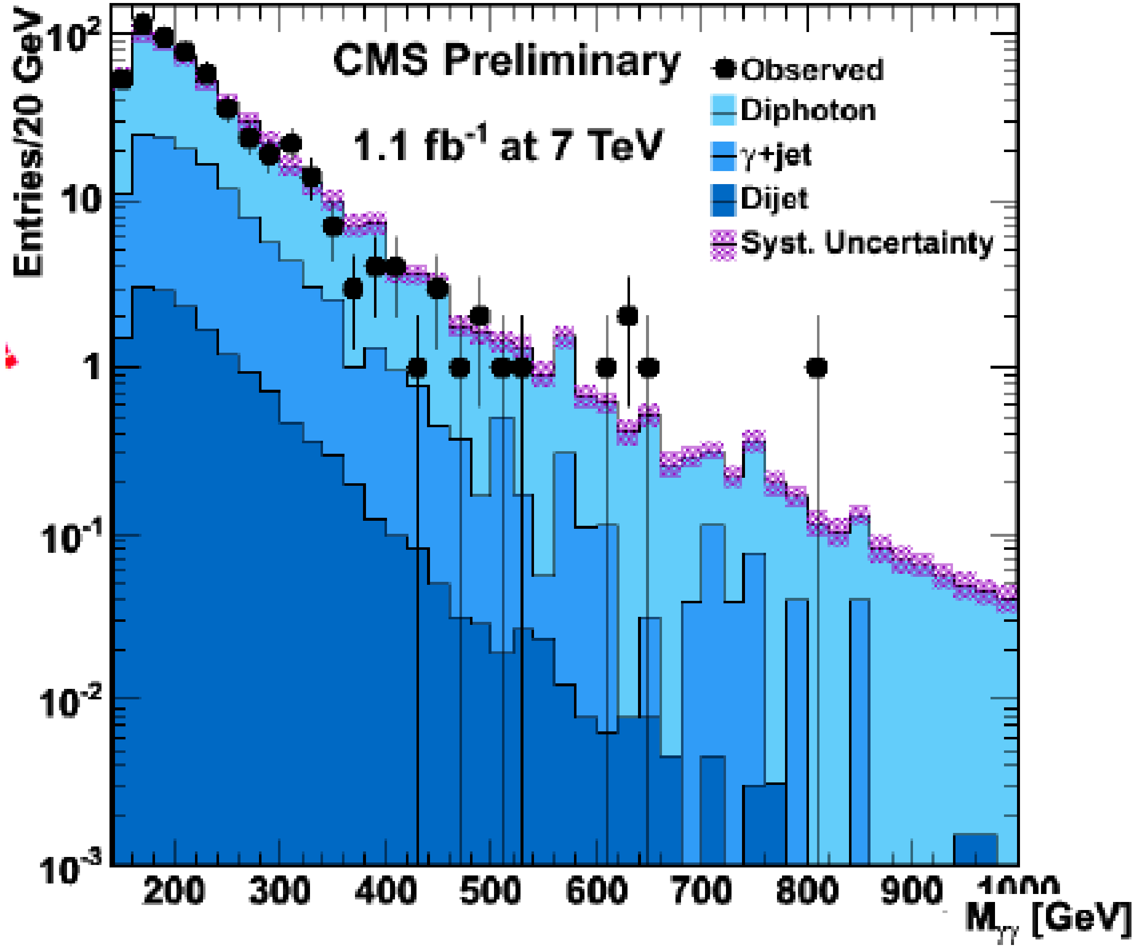
Sequential SM:
m(Z') > 1.9 TeV at 95% C.L.

RS graviton ($k/M_{Pl} = 0.1$):
m(G) > 1.8 TeV at 95% C.L.



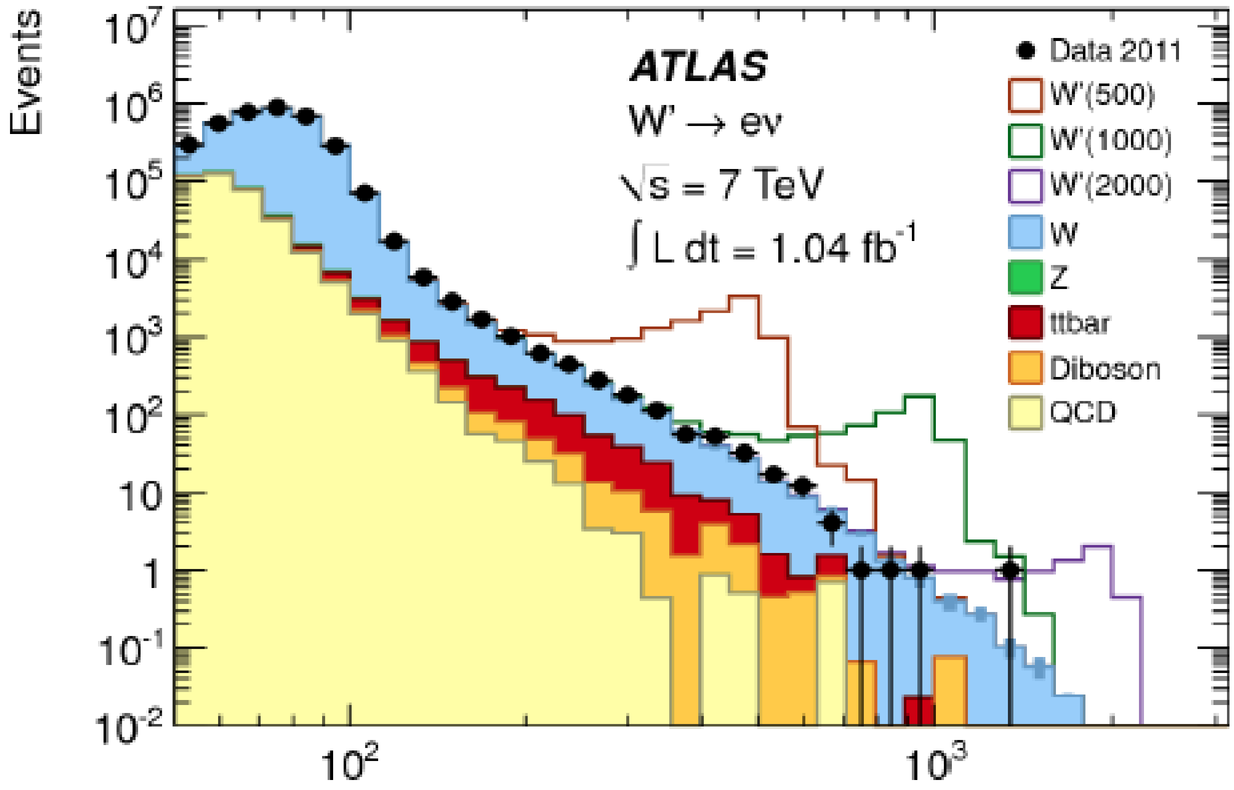
Di-photon Channel

RS graviton (k/MPl = 0.1):
m(G) > 1.7 TeV at 95% C.L.



W′ -> l ν

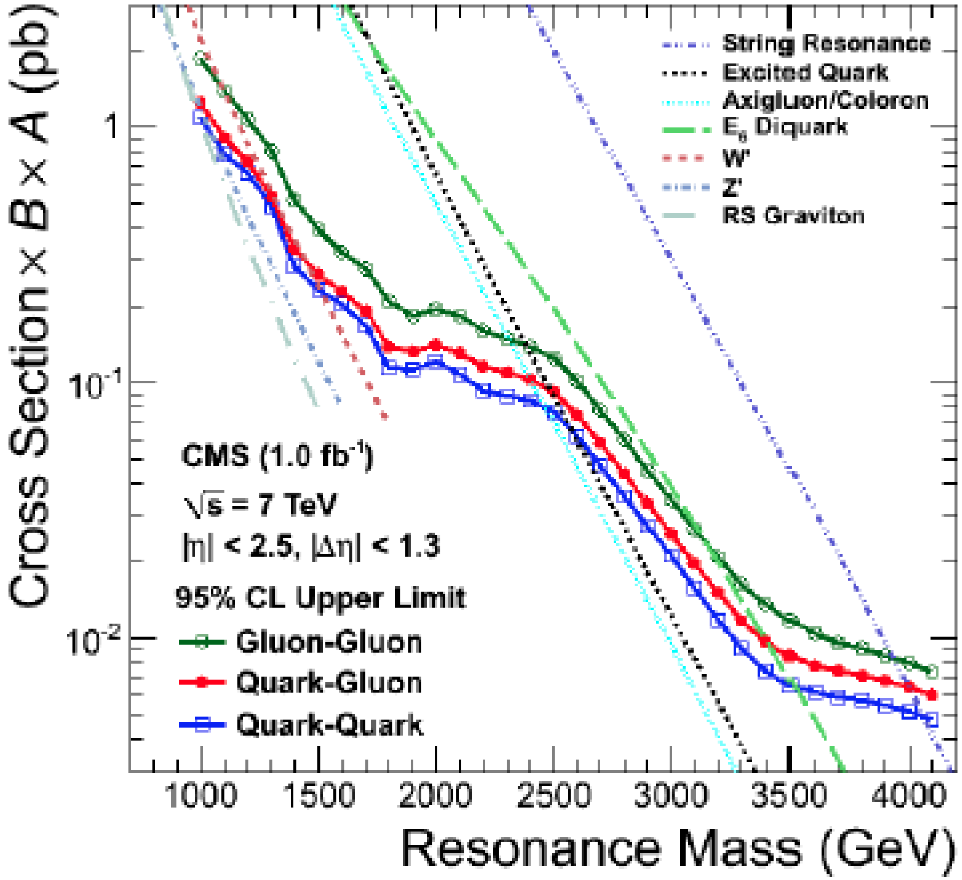
Sequential SM:
m(W') > 2.3 TeV at 95% C.L.



Dijet

Model ATL-CONF-2011-095	95% CL Limits (TeV) Expected	Observed
Excited Quark q^*	2.77	2.91
Axigluon	3.02	3.21
Color Octet Scalar	1.71	1.91

Model CMS arXiv.1107.4771	Excluded Mass (TeV) Observed	Expected
String Resonances	4.00	3.90
E_6 Diquarks	3.52	3.28
Excited Quarks	2.49	2.68
Axigluons/Colorons	2.47	2.66
W′ Bosons	1.51	1.40



SUSY: boson fermion symmetry

The hierarchy problem: $$\delta m^2_{h|top} = -\frac{3G_F}{2\sqrt{2}\pi^2} m_t^2 \Lambda^2 \sim -(0.2\Lambda)^2$$

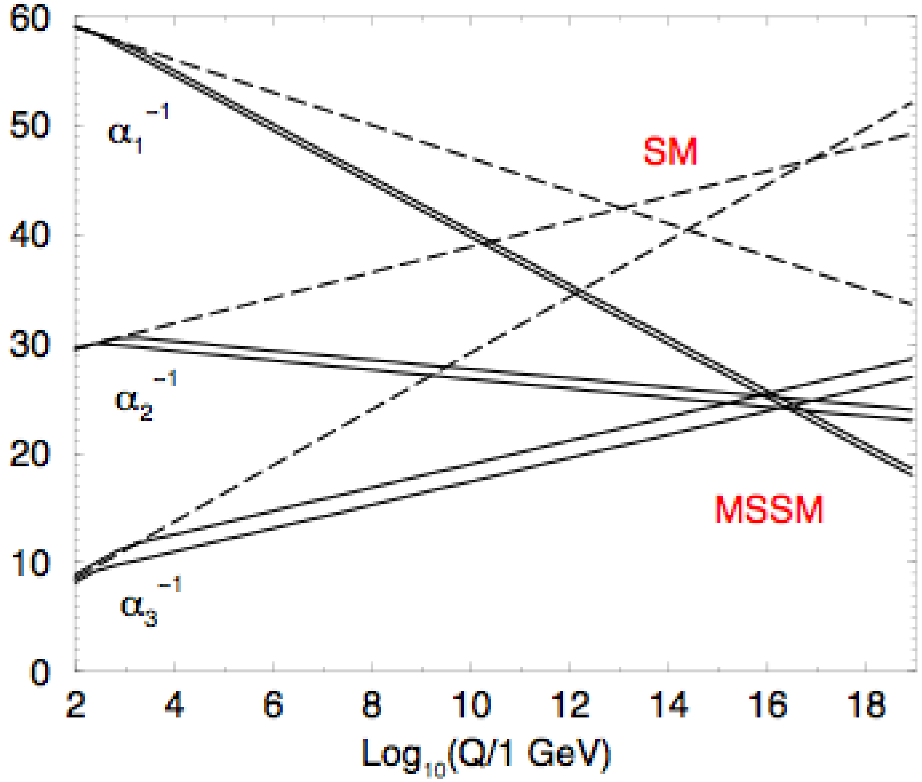
In broken SUSY Λ^2 is replaced by $(m_{stop}{}^2 - m_t{}^2)\log\Lambda$

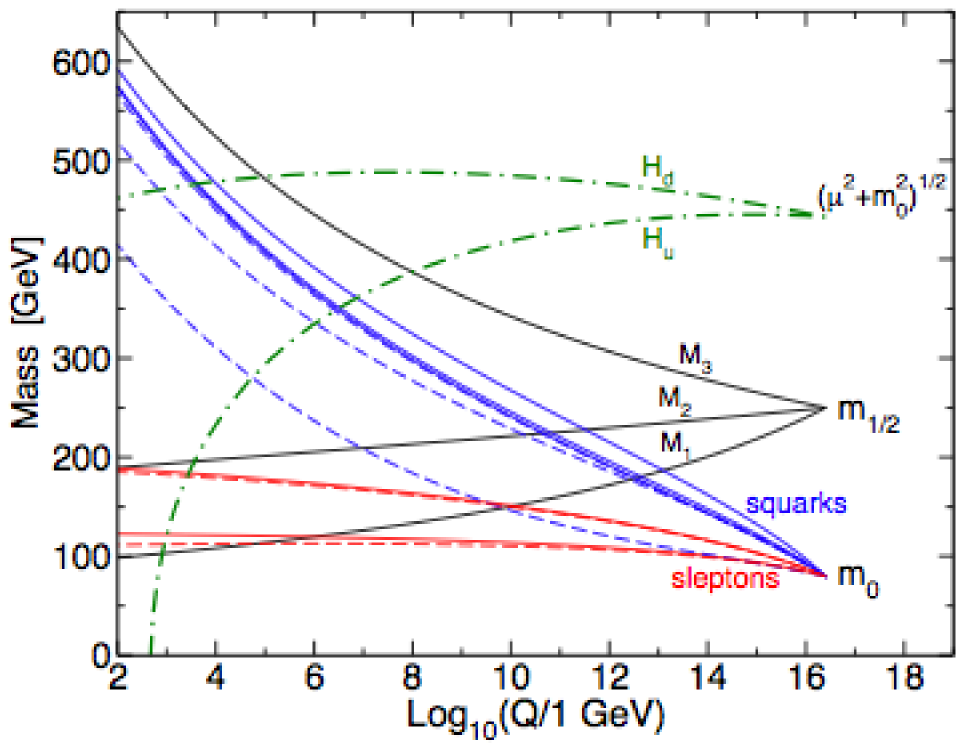
$m_H > 115.5$ GeV, $m_{\chi+} > 100$ GeV, EW precision tests, success of CKM, absence of FCNC, all together, impose sizable Fine Tuning (FT) particularly on minimal realizations (MSSM, CMSSM…).

Yet SUSY is a completely specified, consistent, computable model, perturbative up to M_{Pl} quantitatively in agreement with coupling unification (GUT's)
(unique among NP models)
and has a good DM candidate: the neutralino (actually more than one).

Remains the reference model for NP

Beyond the SM SUSY is unique in providing a perturbative theory up to the GUT/Planck scale





Other BSM models (little Higgs, composite Higgs, Higgsless….) all become strongly interacting and non perturbative at a multi-TeV scale

Nuclear Physics B70 (1974) 39–50. North-Holland Publishing Company

The Wess- Zumino model is the basis for the MSSM, central in the LHC programme

SUPERGAUGE TRANSFORMATIONS IN FOUR DIMENSIONS

J. WESS
Karlsruhe University

B. ZUMINO
CERN, Geneva

Received 5 October 1973

Abstract: Supergauge transformations are defined in four space-time dimensions. Their commutators are shown to generate γ_5 transformations and conformal transformations. Various kinds of multiplets are described and examples of their combinations to new representations are given. The relevance of supergauge transformations for Lagrangian field theory is explained. Finally, the abstract group theoretic structure is discussed.

Volume 49B, number 1 PHYSICS LETTERS 18 March 1974

A LAGRANGIAN MODEL INVARIANT UNDER SUPERGAUGE TRANSFORMATIONS

J. WESS
Karlsruhe University, Germany

and

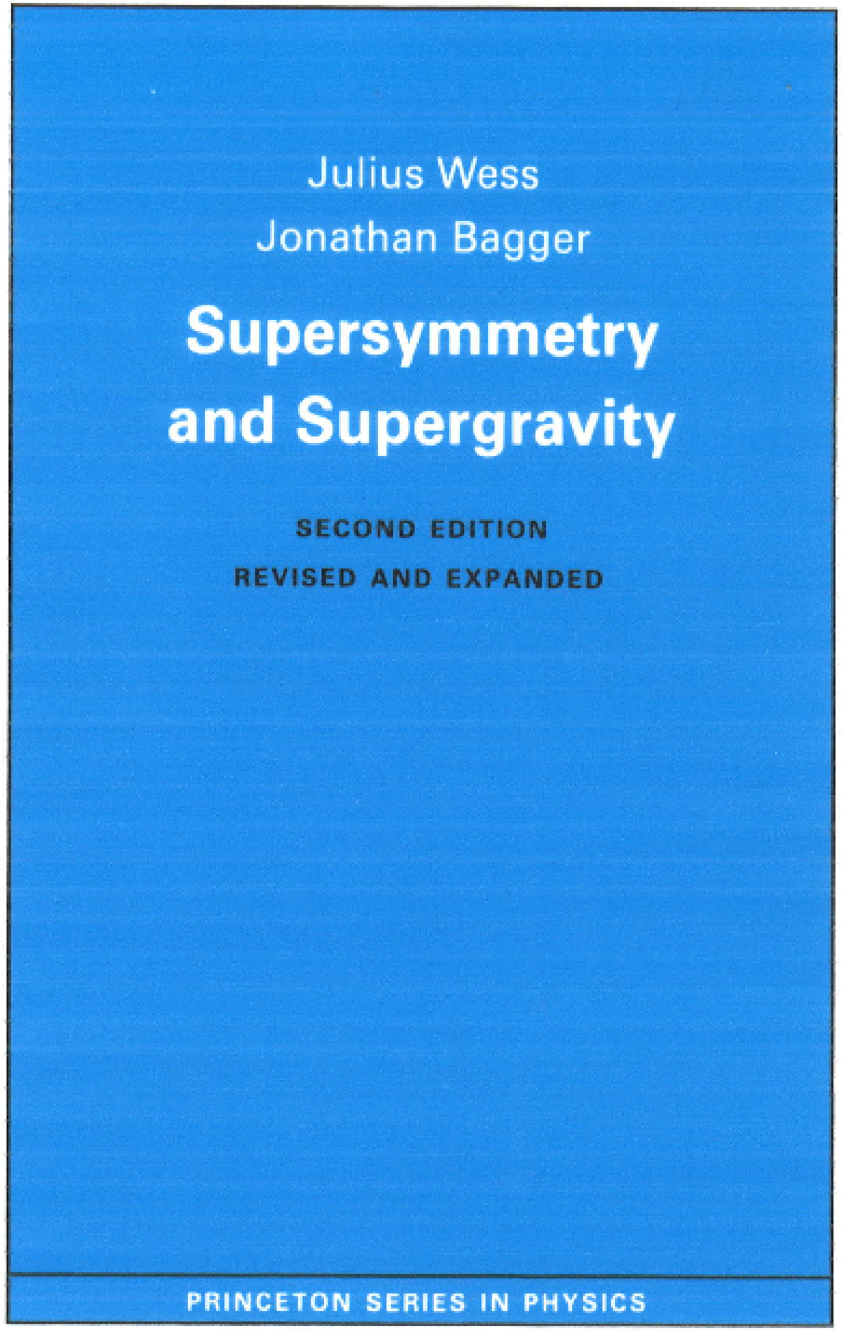
B. ZUMINO
CERN, Geneva, Switzerland

Received 4 January 1974

We study, in the one-loop approximation, a Lagrangian model invariant under supergauge transformations. The model involves a scalar, a pseudoscalar and a spinor field. Supergauge invariance gives rise to relations among the masses and the coupling of these fields and implies the existence of a conserved current. The renormalization procedure is discussed and the relations among masses and couplings are shown to be preserved by renormalization.

Julius Wess: a teacher

Most theorists
have learnt SUSY
from this book



The general MSSM has > 100 parameters

Simplified versions with a drastic reduction of parameters are used for practical reasons, e.g.

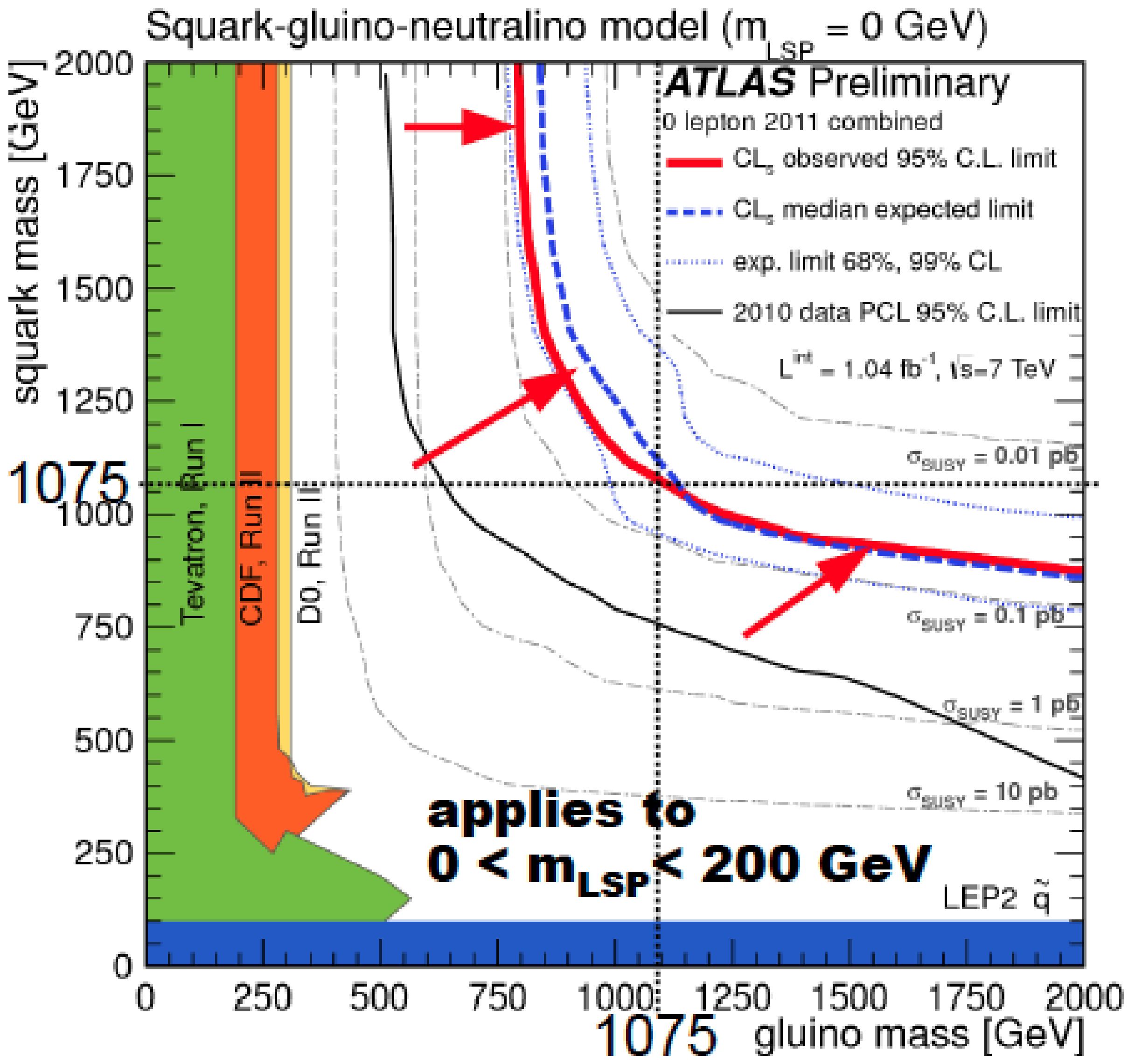
CMSSM, mSUGRA : universal gaugino and scalar soft terms at GUT scale $m_{1/2}$, m_0, A_0, $tg\beta$, $sign(\mu)$

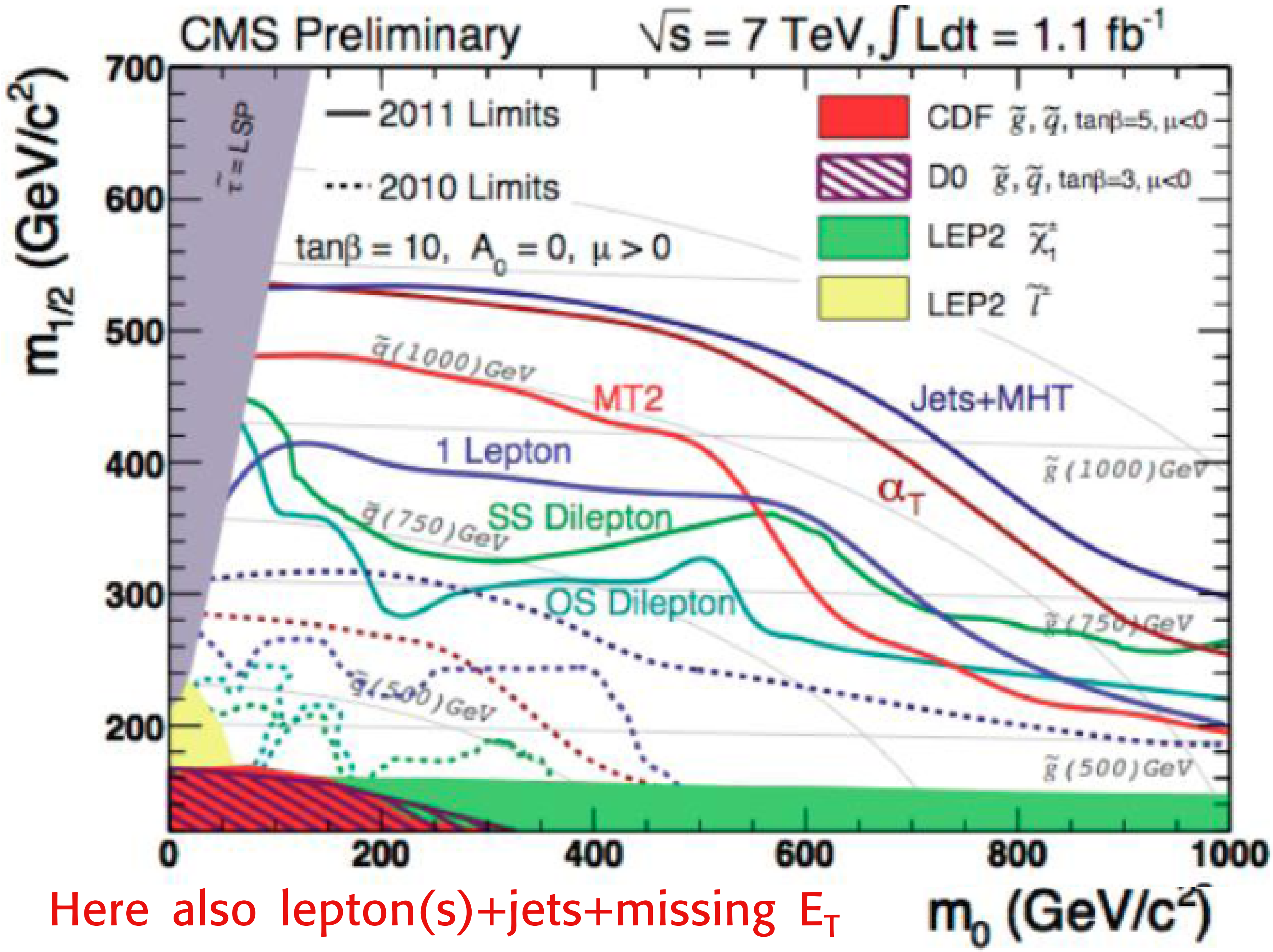
NUHM1,2: different than m_0 masses for H_u, H_d (1 or 2 masses)

It is only these oversimplified models that are now cornered

Jets + missing E_T

CMSSM (degenerate s-quarks)





Here also lepton(s)+jets+missing E_T

Impact of m_H ~ 125 GeV on SUSY models

Simplest models with gauge mediation are disfavoured (predict m_H too light)

Djouadi et al; Draper et al, '11

some versions, eg gauge mediation with extra vector like matter, or with Higgs-messenger mixing do work

Endo et al '11, Evans et al '12

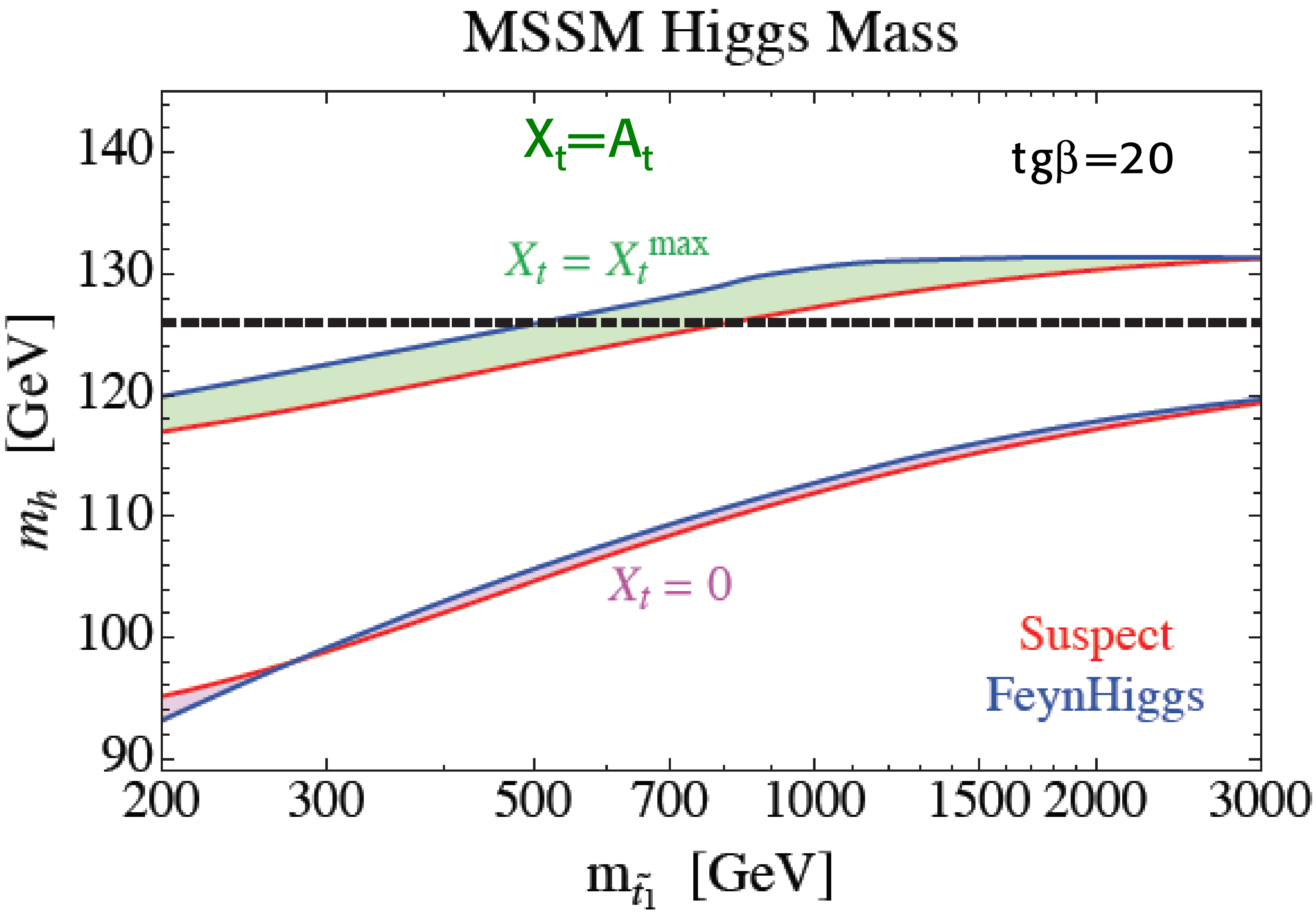
Anomaly mediation is also generically in trouble

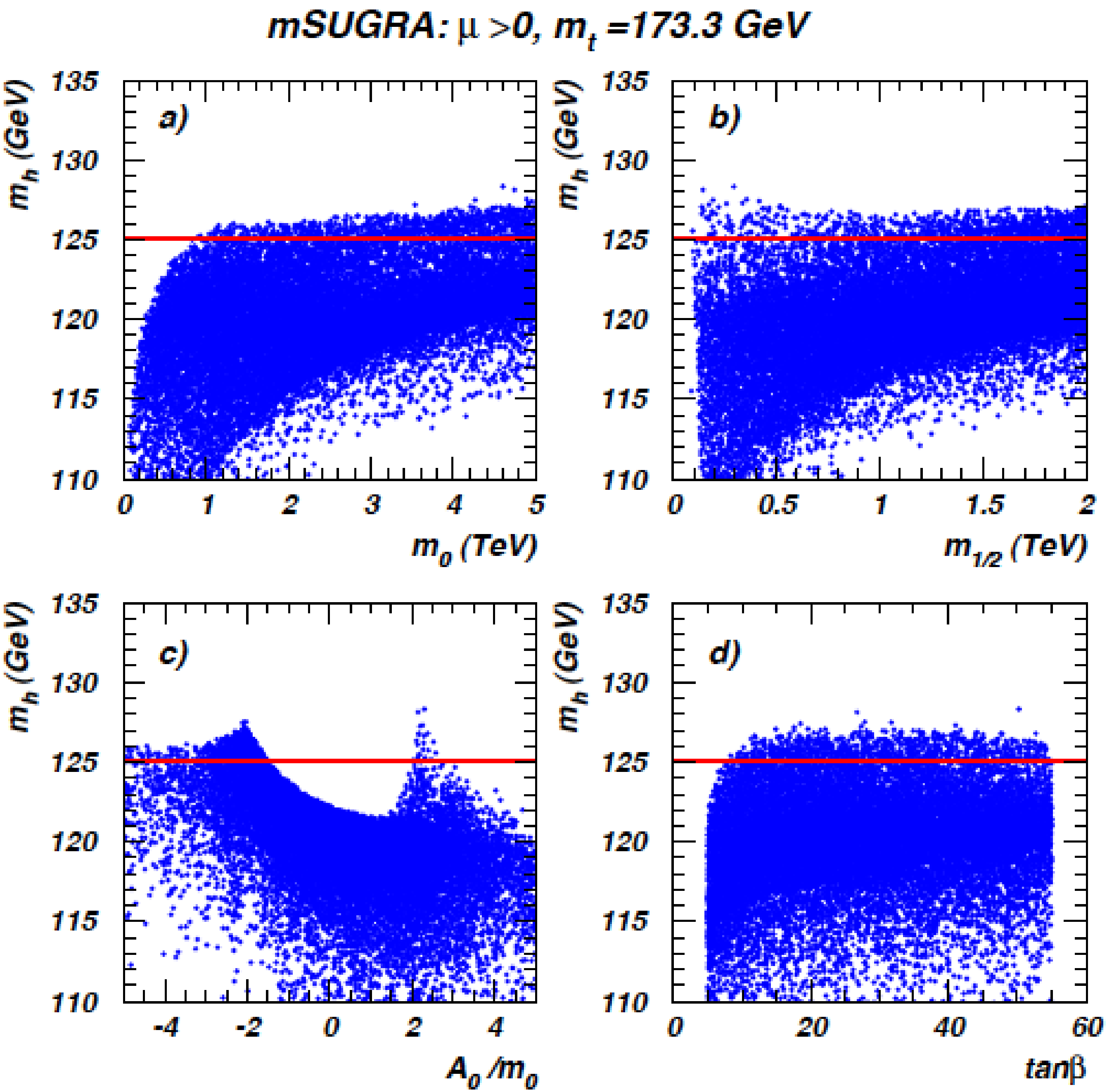
Gravity mediation is better but CMSSM, mSUGRA, NUHM1,2 need squarks heavy, A_t large and lead to tension with g-2 (that wants light SUSY) and $b \to s\gamma$

Akura et al; Baer et al; Battaglia et al; Buchmuller et al,
Kadastik et al; Strege et al; '11

maximal top mixing is required

Hall et al '11



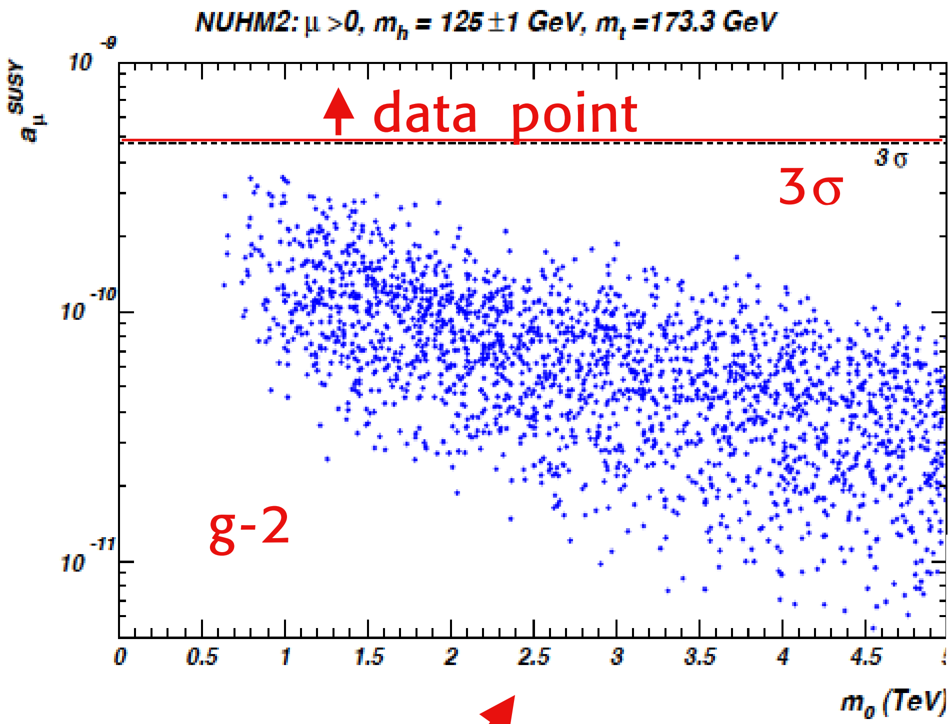

mSUGRA: μ >0, m_t =173.3 GeV
a)
b)
c)
d)
m_h (GeV)
135
130
125
120
115
110
0 1 2 3 4 5
m_0 (TeV)
0 0.5 1 1.5 2
m_1/2 (TeV)
-4 -2 0 2 4
A_0 /m_0
0 20 40 60
tanβ

Baer et al '11

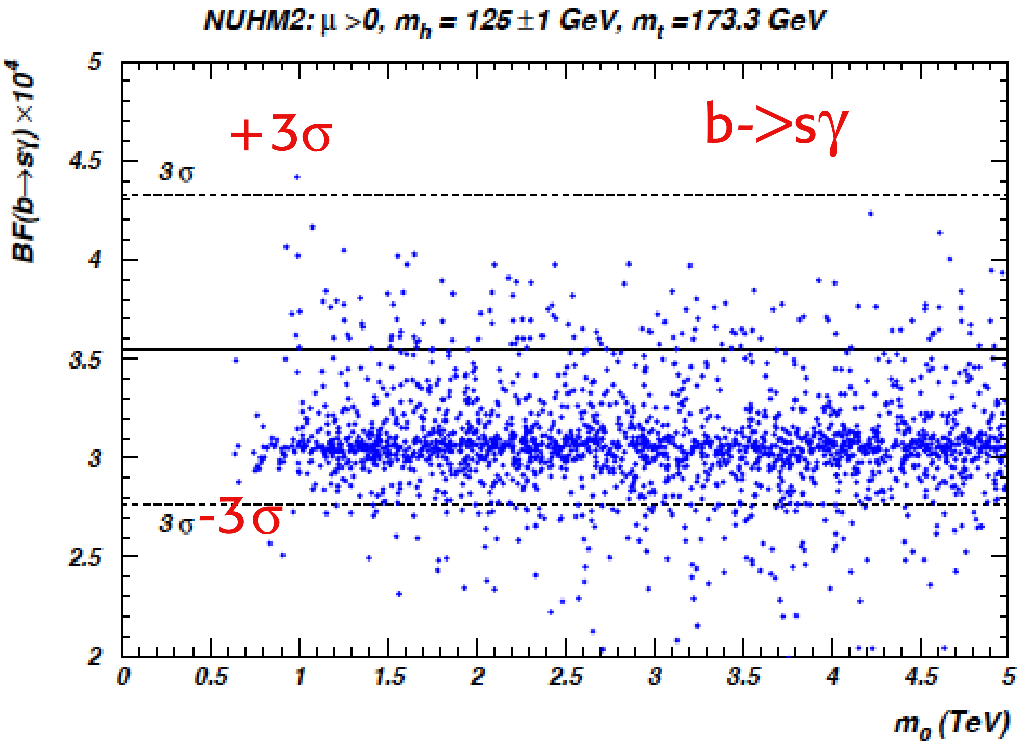
Baer et al '11

NUHM1,2

add 1 or 2 separate mass parameters for Hu, Hd



Serious tension between g-2 and m_H ~ 125 GeV in CMSSM, mSUGRA, NUHM1,2



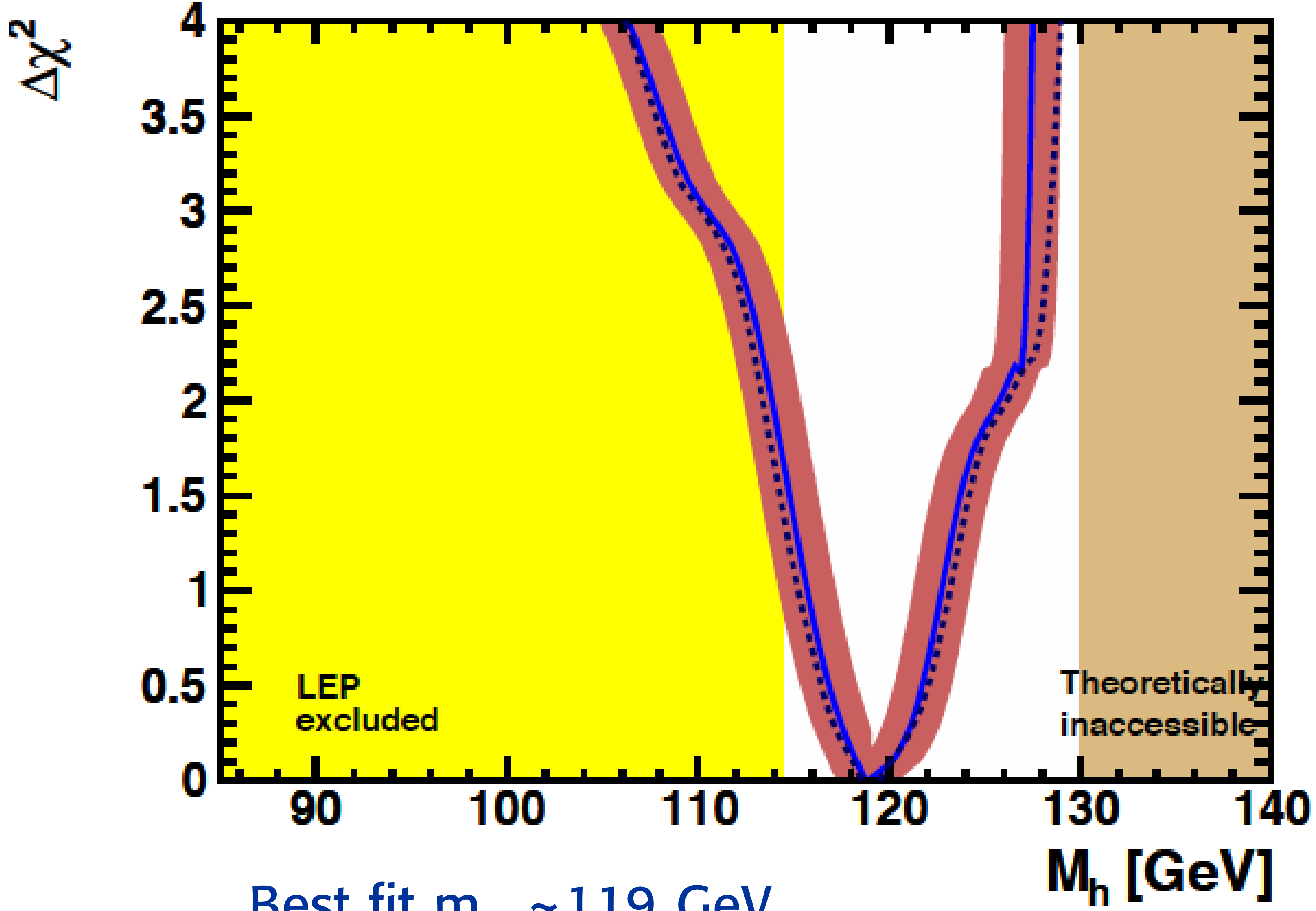
Input data for existing fits of CMSSM, NUHM1 ...... include

- The EW precision tests
- Muon g-2
- Flavour precision observables
- Dark Matter
- Higgs mass constraints and LHC

e.g.
MASTERCODE
Buchmuller et al

Pre LHC '11 fit

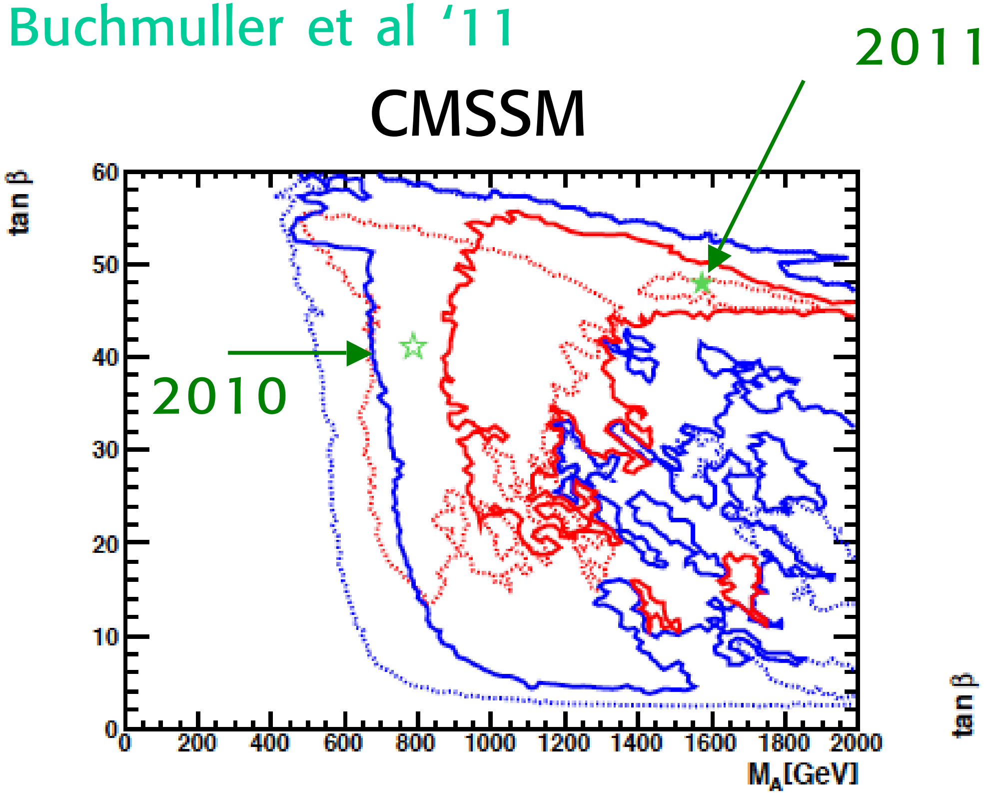
Buchmuller et al '11



Best fit m_H ~119 GeV

Buchmuller et al '11

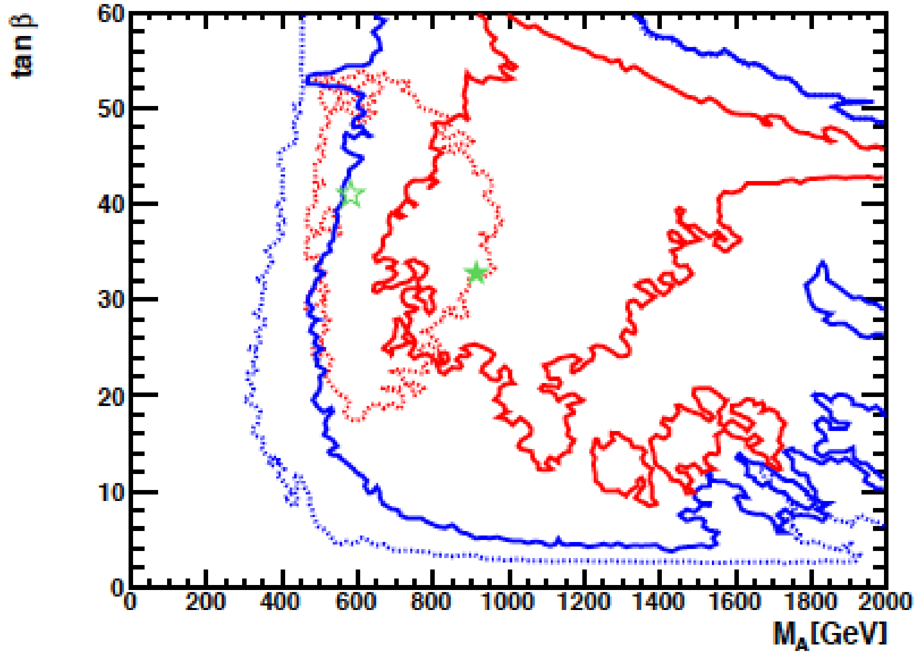
CMSSM



With 2011 LHC data heavier scalars

Tension
g-2 vs m_H ~ 125 GeV

NUHM1



with g-2 m_H ~ 119 GeV
without g-2 m_H ~ 125 GeV

g-2 indicates light SUSY!!

SUSY

With new data ever increasing fine tuning

One must go to SUSY beyond the CMSSM, mSUGRA, NUHM1,2

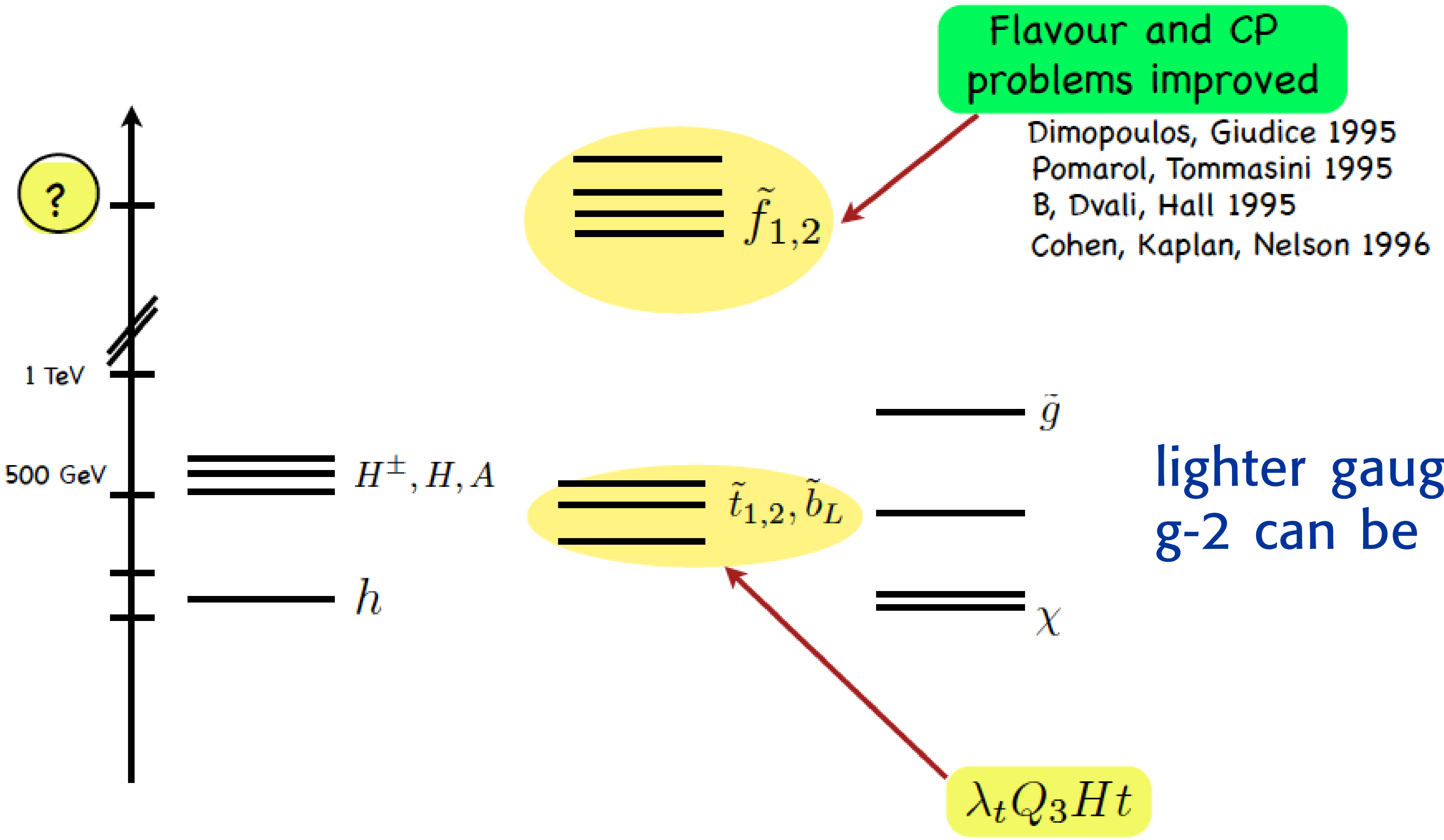
There is still room for more sophisticated versions

- Heavy first 2 generations
- NMSSM
- λ SUSY
- Split SUSY
- Large scale SUSY
- • • •

Beyond the CMSSM, mSugra, NUHM1,2

Heavy 1st, 2nd generations

Barbieri

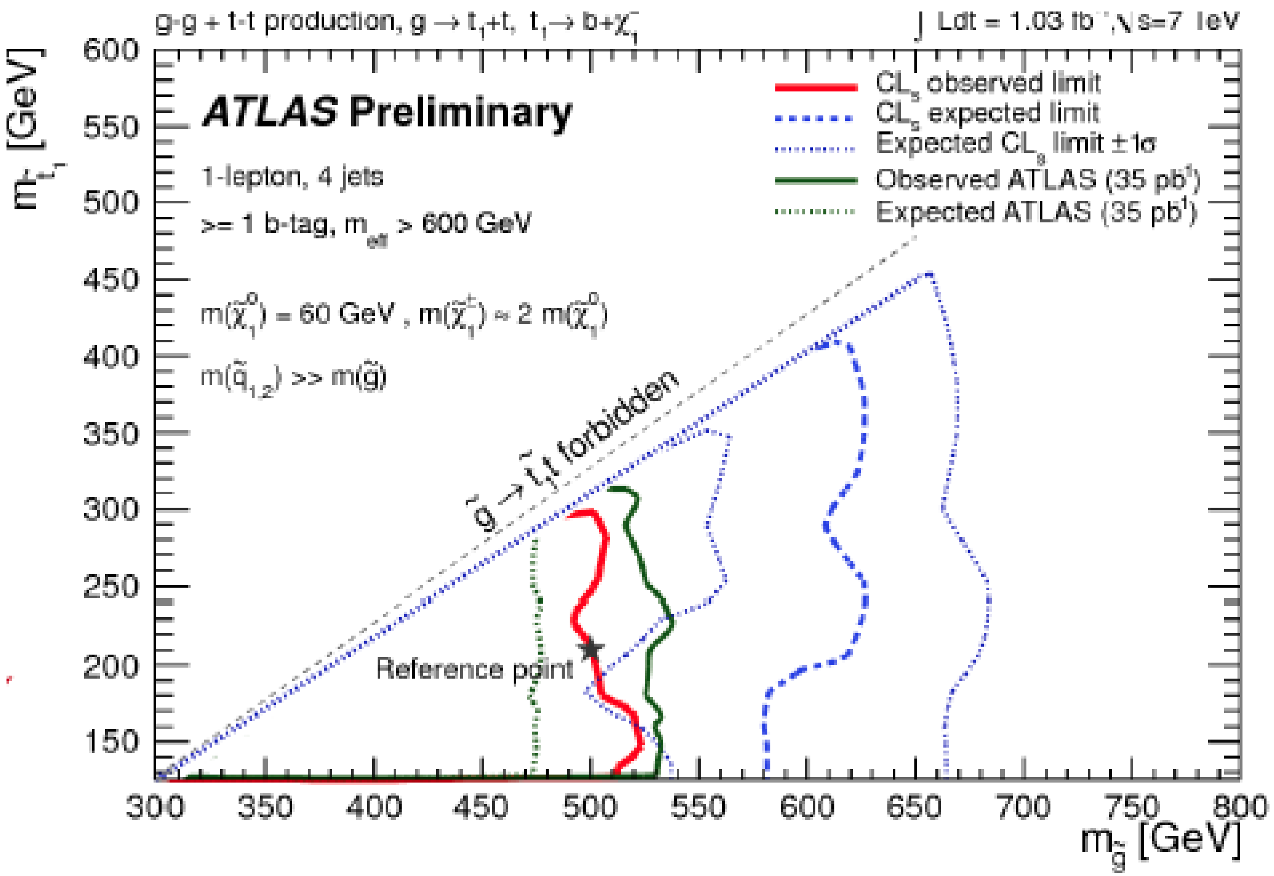


lighter gauginos,
g-2 can be rescued

For example, may be gluinos decay into 3-gen squarks

e.g. $\tilde{g} \to \tilde{t}_1 t$; $\tilde{t}_1 \to b\tilde{\chi}_1^{\pm}$

and $\tilde{\chi}_1^{\pm} \to W^* \tilde{\chi}_1^0$



m(gluino) > 500 GeV at 95% C.L.

$m_{s\text{-}top}$ >~250 GeV

An extra singlet Higgs

In a promising class of models a singlet Higgs S is added and the μ term arises from the S VEV (the μ problem is solved)

$$\lambda\, S H_u H_d$$

Mixing with S can bring the light Higgs mass down at tree level

(no need of large loop corrections)

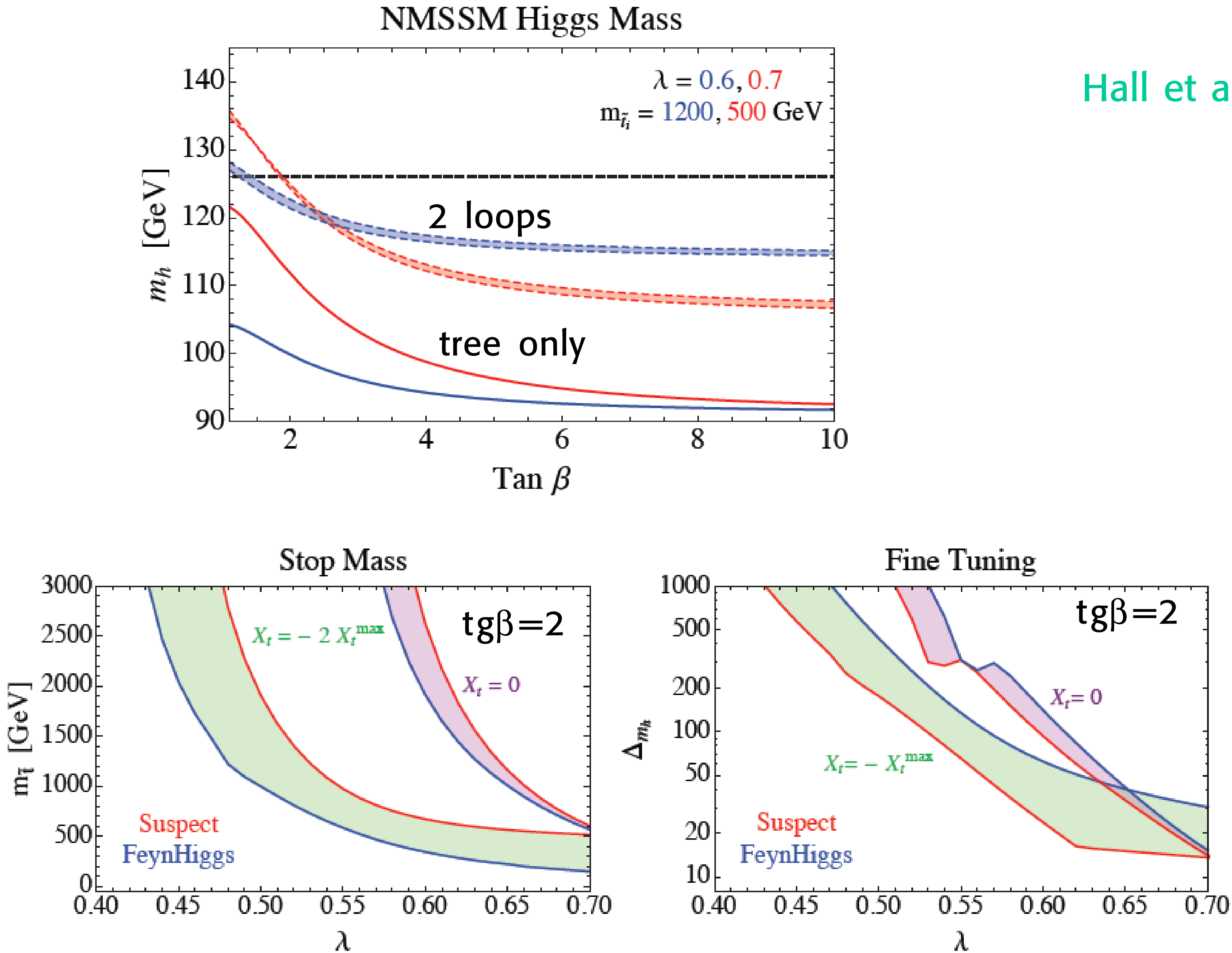
Depending on the value of λ:

NMSSM: $\lambda < \sim 0.7$ the theory remains perturbative up to M_{GUT}
(no need of large stop mixing, less fine tuning)

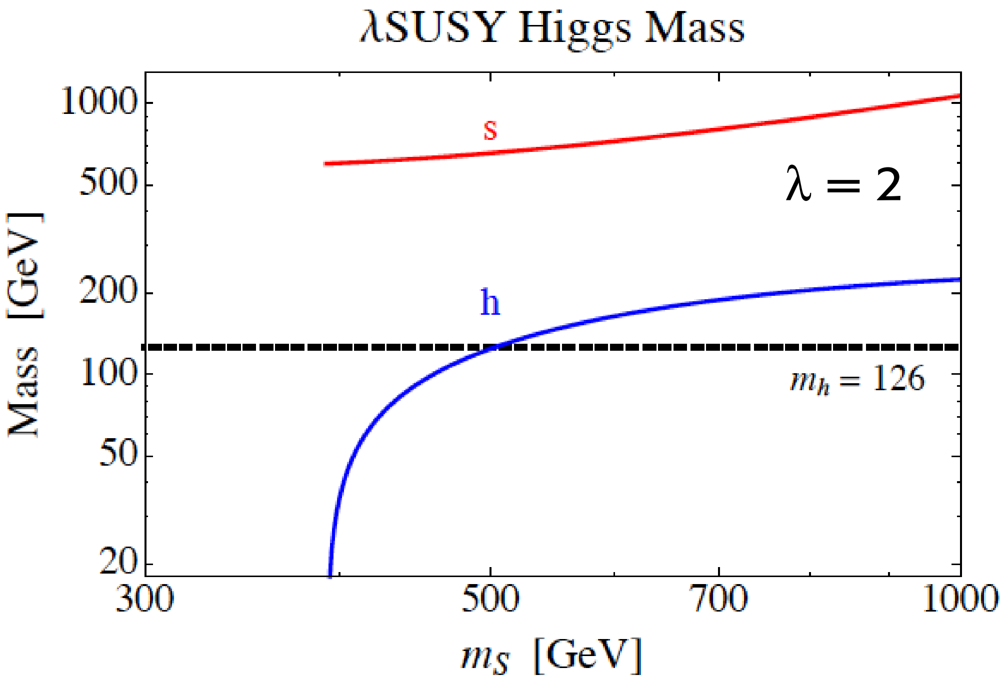
Arvanitaki et al, Hall et al '11, King et al '12

λ SUSY: $\lambda \sim 1 - 2$ for $\lambda > 2$ theory non pert. at ~10 TeV

Hall et al '11


NMSSM Higgs Mass
λ = 0.6, 0.7
$m_{\tilde{t}_i}$ = 1200, 500 GeV
2 loops
tree only
m_h [GeV]
Tan β
Stop Mass
$X_t = -2\,X_t^{max}$
$X_t = 0$
tgβ=2
$m_{\tilde{t}}$ [GeV]
Suspect
FeynHiggs
λ
Fine Tuning
tgβ=2
$X_t = 0$
$X_t = -X_t^{max}$
Δ_{m_h}
Suspect
FeynHiggs
λ

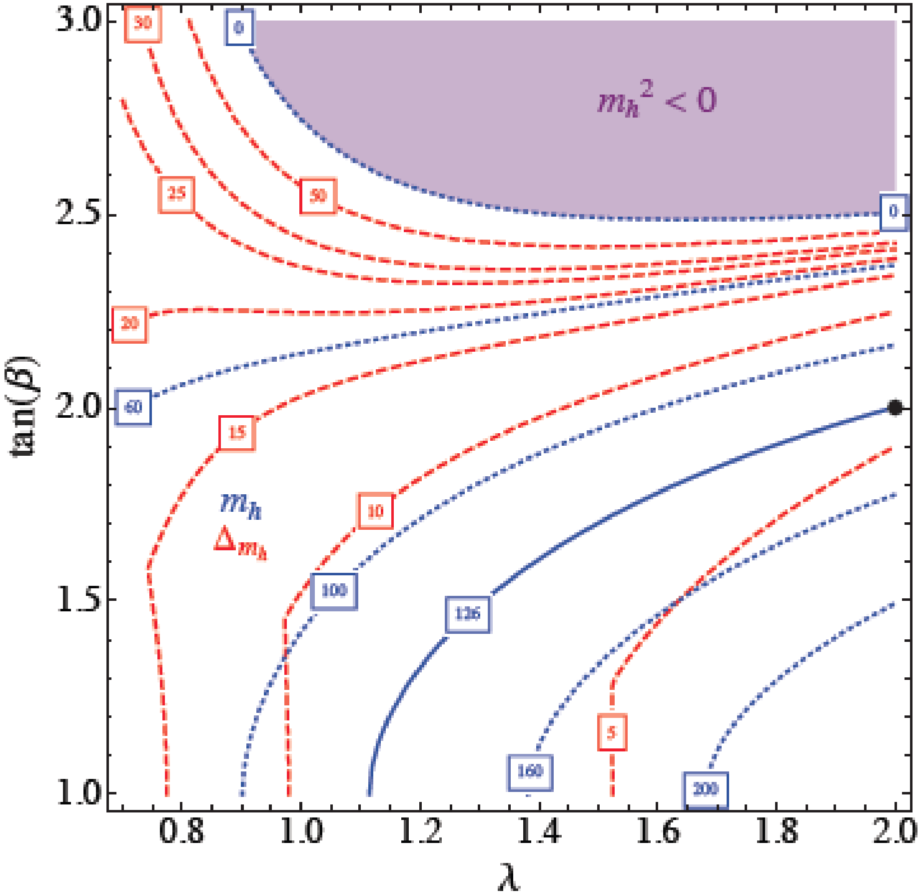
Hall et al '11



Mixing with S makes h light already at tree level

No need of loops

Fine tuning can be very small

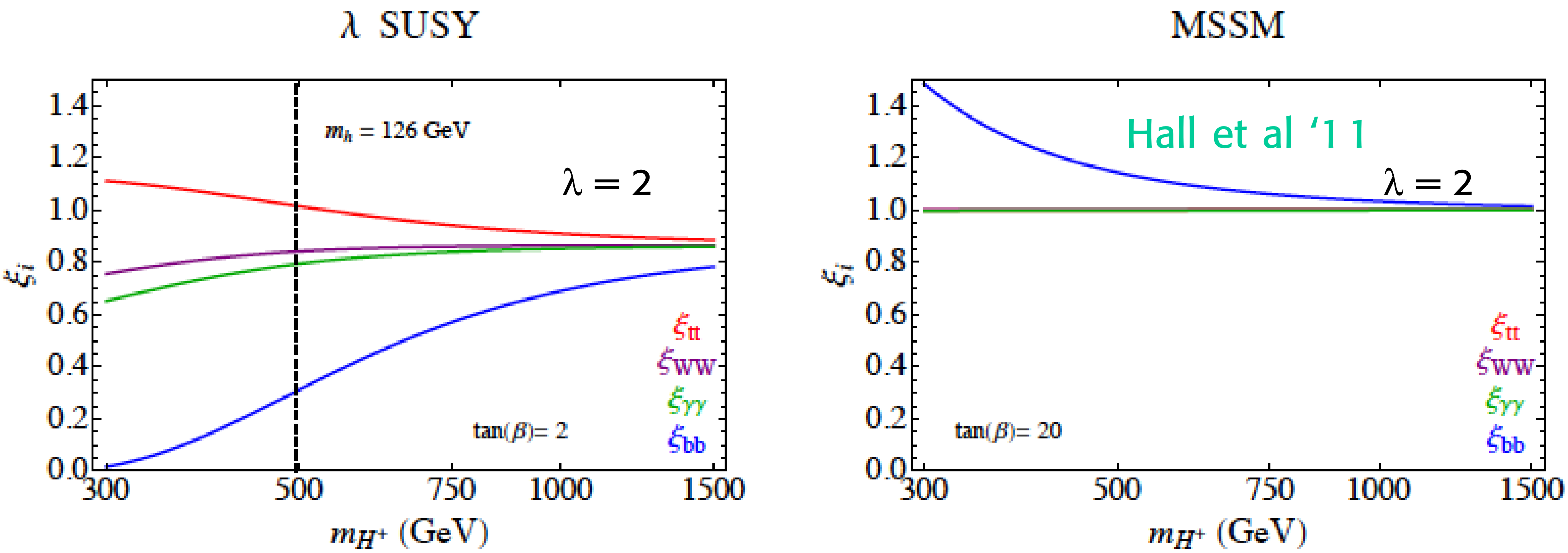


It is not excluded that at 125 GeV you see the heaviest of the two and the lightest escaped detection at LEP

Ellwanger '11

In MSSM it is not possible to obtain an enhanced $\gamma\gamma$ signal for m_H ~ 125 GeV, while it is possible eg in NMSSM or λ SUSY

Arvanitaki et al, Hall et al '11



Drawback of λ SUSY: relation with GUT's & coupling unification is generically lost

Conclusion

LHC scenarios

Catastrophic: No Higgs, no new physics

Can only occur if the LHC is not enough to fully probe the EW scale: unitarity violations impose one or the other (eg new vector bosons) or both

The Higgs comes closer: yes or no to the SM Higgs in 2012
Hints (to be confirmed) of $m_H \sim$ 125 geV

Theorist projection: non standard Higgs and new physics

A lot of model building in this direction

No new Physics so far: but LHC is just at beginning

Pure SM: A light scalar Higgs, no new physics at the LHC

If so, nature does not at all abhor fine tuning

This is the anthropic paradigm that experiment must try to falsify