Higgs Hunting, Paris, 27 June ‘13

Theoretical Concluding Talk

Guido Altarelli
Roma Tre/CERN

LHC 7-8 TeV

A great triumph: the 126 GeV Higgs discovery

A particle apparently just as predicted by the SM theory

The main missing block for the experimental validation of the SM is now in place

A negative surprise: no production of new particles, no evidence of new physics

Not at ATLAS&CMS although
a big chunk of new territory has been explored
Not in HF decays (LHCb, ... B-factories)
[Nor in $\mu \to e\gamma$ (MEG),.... Perhaps a deviation in $(g-2)_\mu$?]

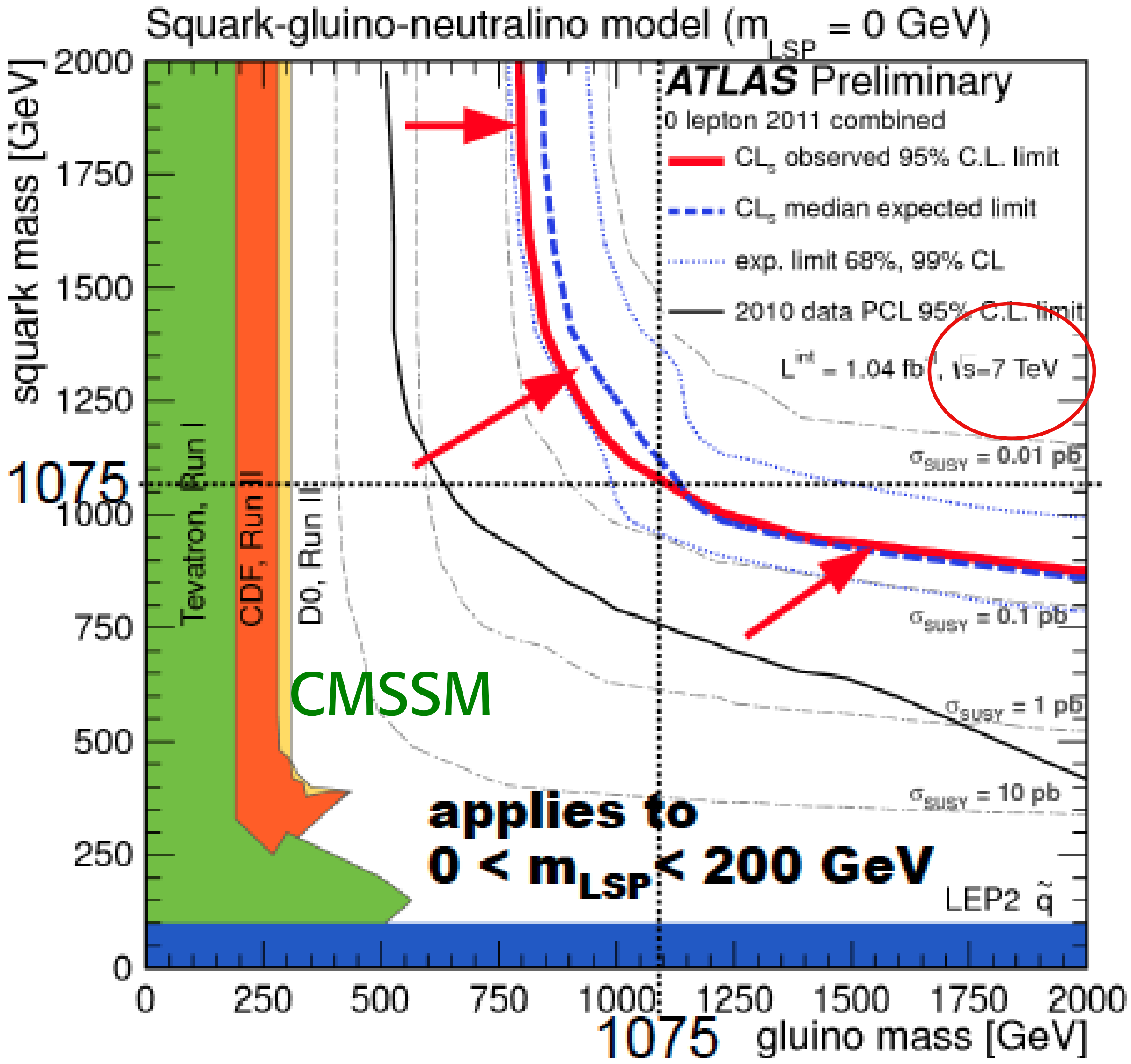
A large new territory explored at the LHC and no new physics

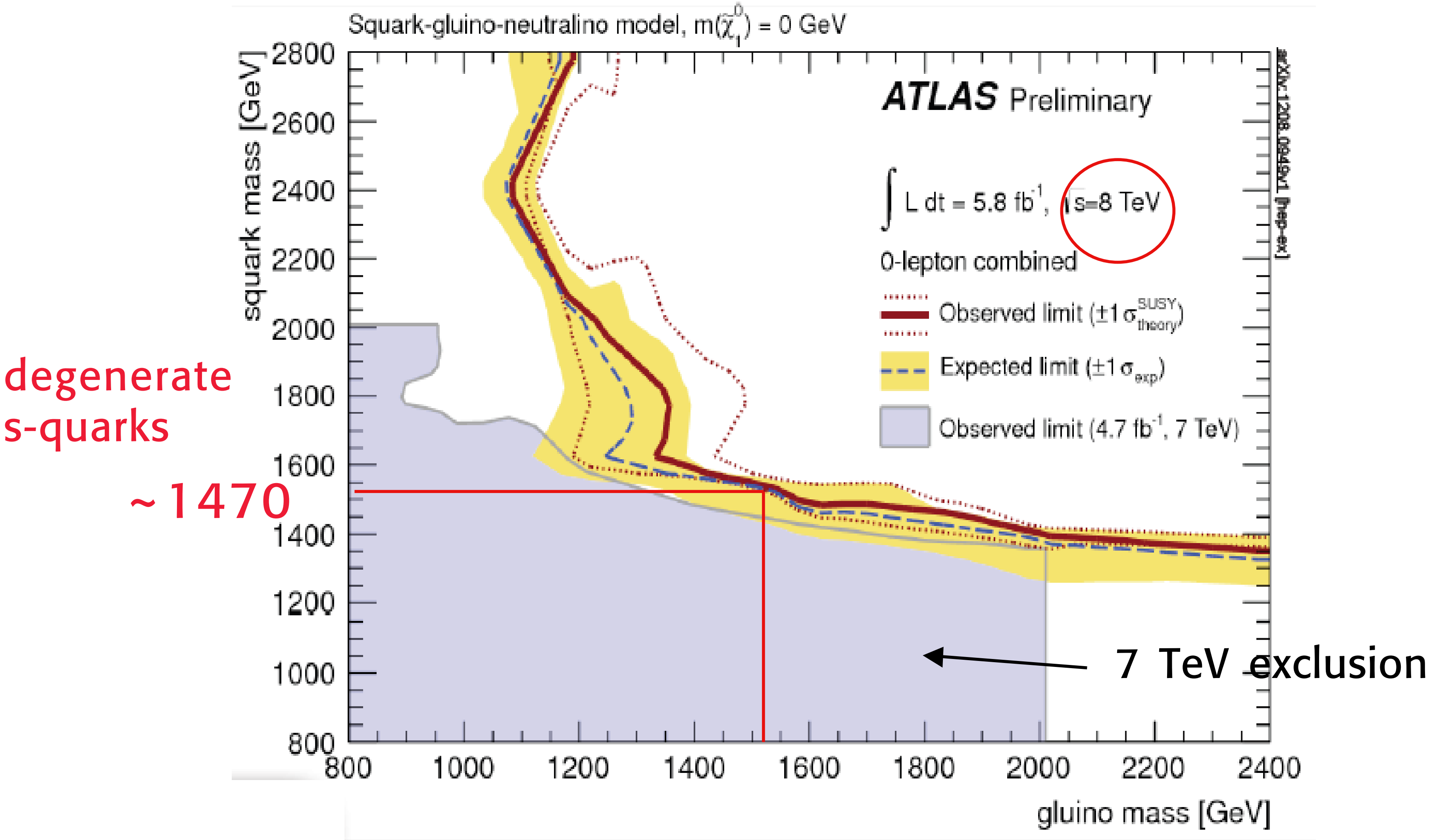
A big step from the
Tevatron 2 TeV
up to LHC 7-8 TeV
(-> 13-14 TeV)

This negative result
is perhaps depressing
but certainly brings
a very important input
to our field

a big change
in perspective

Jets + missing E_T





New physics can appear at any moment but it is now conceivable that no new physics will show up at the LHC

Naturalness? The big question mark!

Flavour is also very stringent (great new results from LHCb, CMS...)

The constraints from flavour physics are extremely demanding: adding effective operators to SM generally leads to very large Λ

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

Nir
Isidori
.....

c_{NP}:

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

The SM is very special and if there is New Physics, it must be highly non generic eg in Minimal Flavour Violation (MFV) models or $U(2)^3$ or..........

Barbieri

The theorists great contribution to the LHC

A large amount of theoretical work was devoted to directly prepare the interpretation of LHC experiments

- New and improved generators for event simulation Frederix
- Advanced QCD and EW calculations Melnikov
- Jet finding, grooming, pruning.... Soyez

In this class one can also include

- QCD lattice calculations for flavour physics and heavy ion experiments

Great progress in computation techniques

Examples of recent NLO calculations in pp collisions

ttbb Bredenstein et al '09-'10, Bevilacqua et al '09
ttW K. Ellis, Campbell '12
W+3jets Berger et al '09, R.K.Ellis , Melnikov, Zanderighi '09,
Z,γ^* +3jets Berger et al '10
WW+2jets Melia et al '10-'11, Jager, Zanderighi '12
WWbb Denner et al '10
tt+2jets Bevilacqua et al '10-'11
bbbb, jjjj Greiner et al '11, Bern et al '11
W, Z+4jets Berger et al '11, Bern et al '12; W+5jets Bern et al '12
....

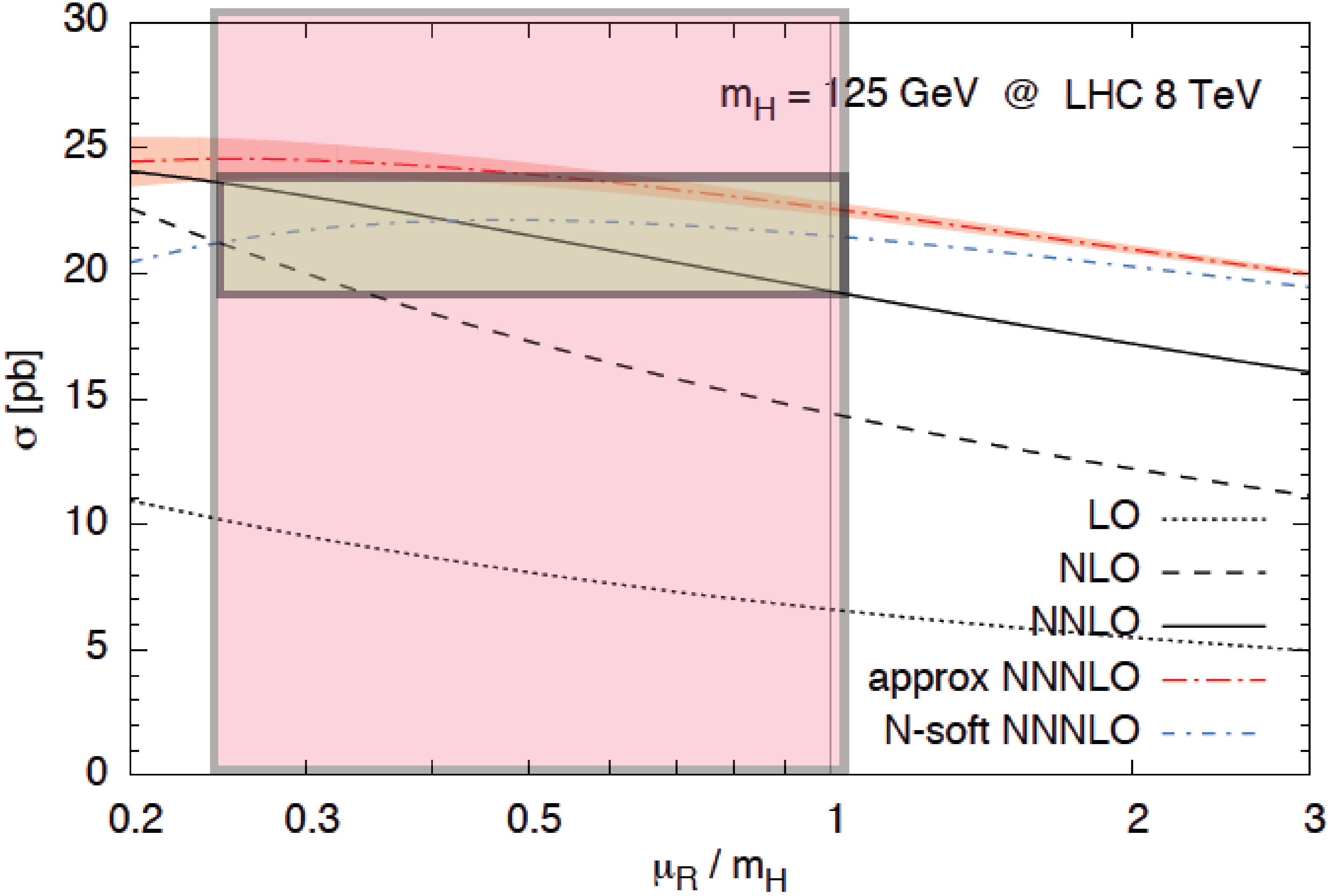
And the Higgs cross section and distributions are known to NNLO Harlander, Kilgore '02; Anastasiou, Melnikov '02; Ravindran et al '03; Anastasiou, Melnikov, Petriello '04, Bozzi et al '07 NNNLO in progress!

A terrific amount of work by QCD theorists for LHC

H inclusive g-g production

Melnikov
Sargsyan

Large K factor



Any SM process at NLO can be processed

Frederix

Available NLO+PS codes

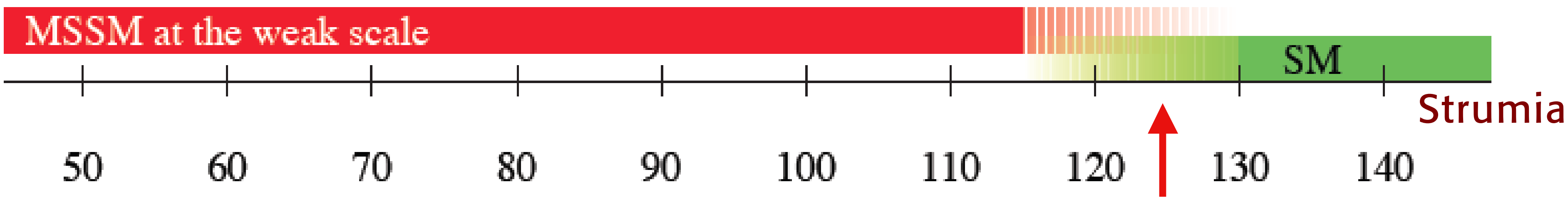
	NLO + PS	Parton Shower	Processes	Merging multiplicities at NLO
MC@NLO	Yes	Herwig 6 and Herwig++	Library for key SM processes	No
aMC@NLO	Yes	Herwig6, Herwig++, Pythia6 and Pythia8*	Code generation allows for any SM process, including simple BSM extensions	Yes, FxFx merging
POWHEG BOX	Yes	All*	Large library of processes; implementing new processes is relatively easy	Yes, MiNLO (without merging scale for simple processes)
SHERPA	Yes	Sherpa	Needs virtual corrections from external code	Yes, MEPS@NLO

The Higgs epochal discovery

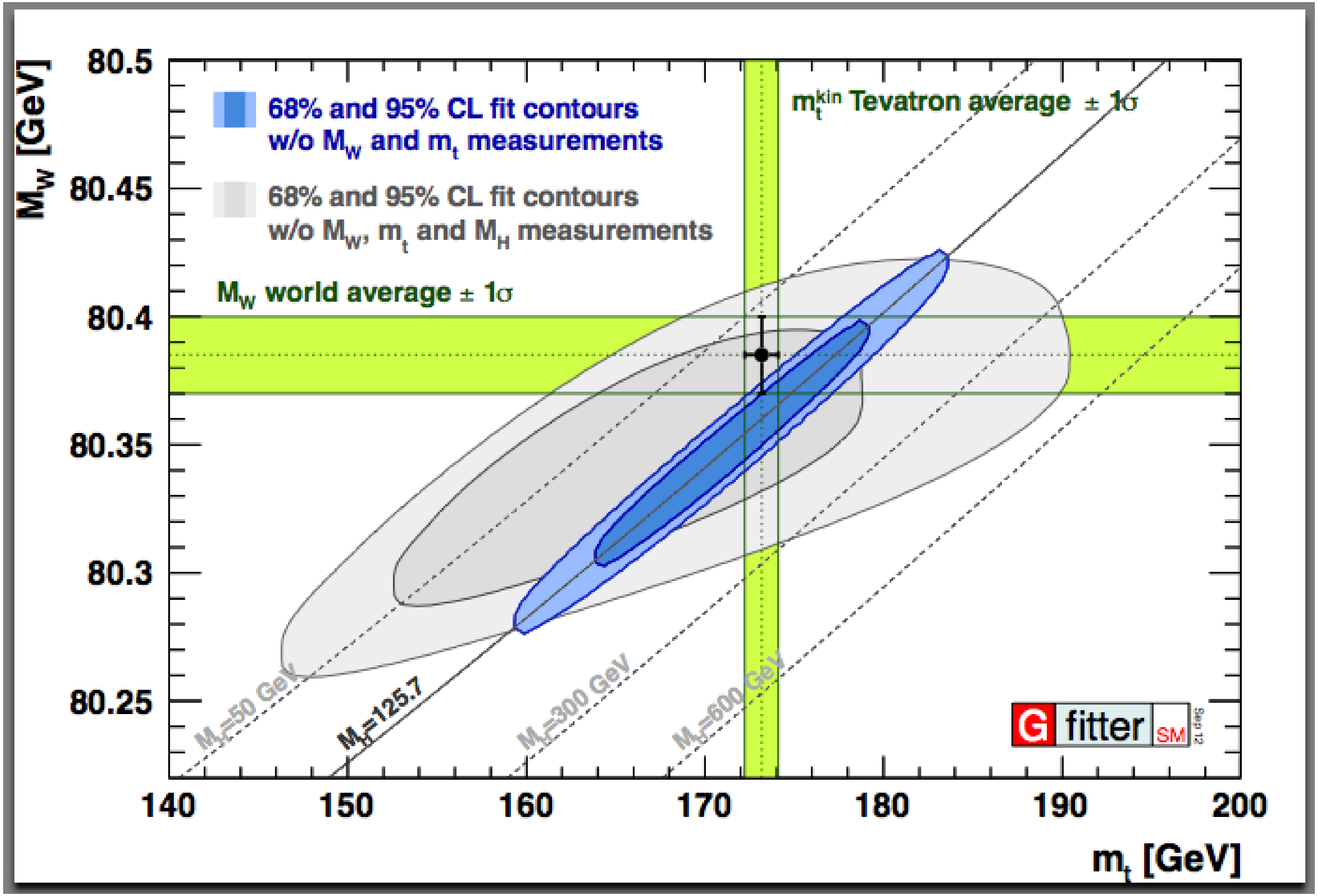
m_H ~ 126 GeV is compatible with the SM and also with the SUSY extensions of the SM

A malicious choice!

$m_H = 125.6 \pm 0.4$ GeV



m_H ~126 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
(in fact no "conspirators" have been spotted: no new physics)



68% and 95% CL fit contours
w/o M_W and m_t measurements
68% and 95% CL fit contours
w/o M_W, m_t and M_H measurements
M_W world average ± 1σ
m_t^kin Tevatron average ± 1σ
M_H=50 GeV
M_H=125.7
M_H=300 GeV
M_H=600 GeV
G fitter SM
Sep 12
M_W [GeV]
m_t [GeV]
80.5
80.45
80.4
80.35
80.3
80.25
140
150
160
170
180
190
200

Is it really the SM Higgs boson?

Are there non SM admixtures?

The next challenge!

- Confirm $J^{PC}=0^{++}$

- Precise measurement of couplings

- Heavier Higgs-like particles? 2HDM, MSSM?

$J^{PC}=0^{++}$?

Muehlleitner

Important to check directly, but other choices would change the interaction vertices and heavily affect rates

H -> $\gamma\gamma$ implies that the H spin cannot be 1 by angular momentum and Bose statistics (s=0,2 can go via s-wave)

With sufficient statistics the spin can be determined by distributions of H - > $\gamma\gamma$ or ZZ*-> 4leptons, or WW* - > 4leptons

Buszello et al, Choi et al '02; De Rujula et al '10; J. Ellis, Hwang'12 ; Djouadi et al '13; De Boer et al '13.........

Information also via the HZ inv mass distributions

J. Ellis, Hwang, Sanz, You,'12...

CP-odd component, CP violating decays: open challenge

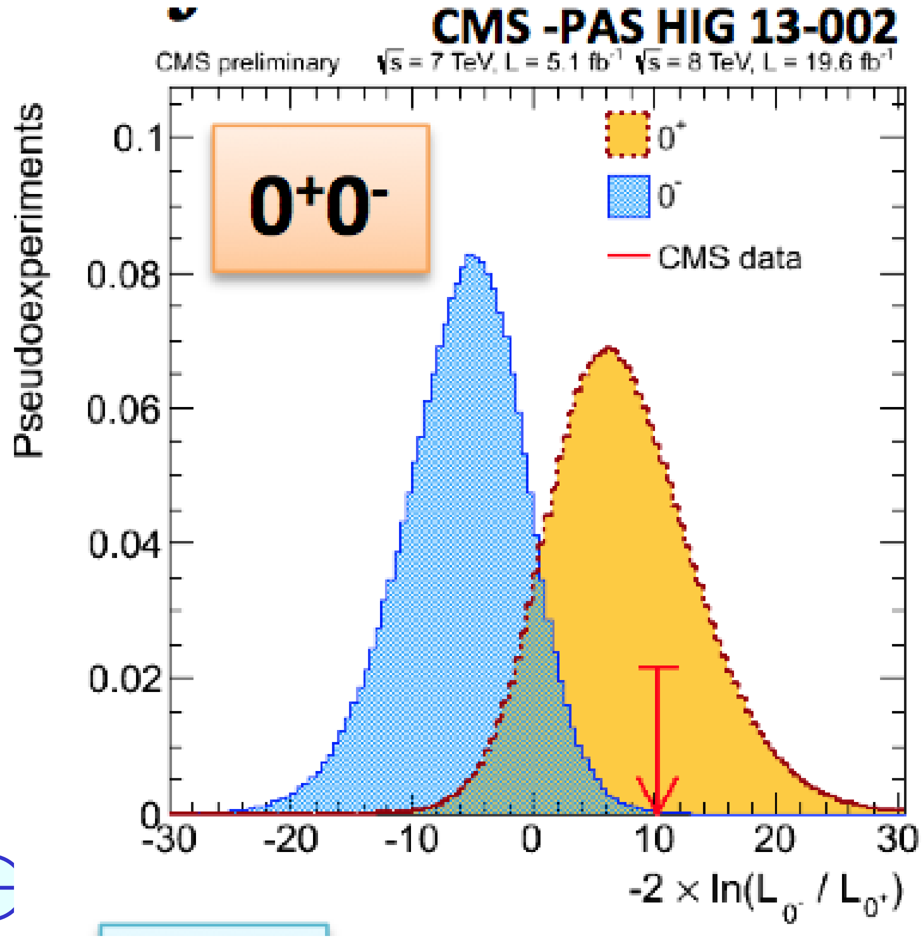
Soni; Freitas; Godbole, Hagiwara......

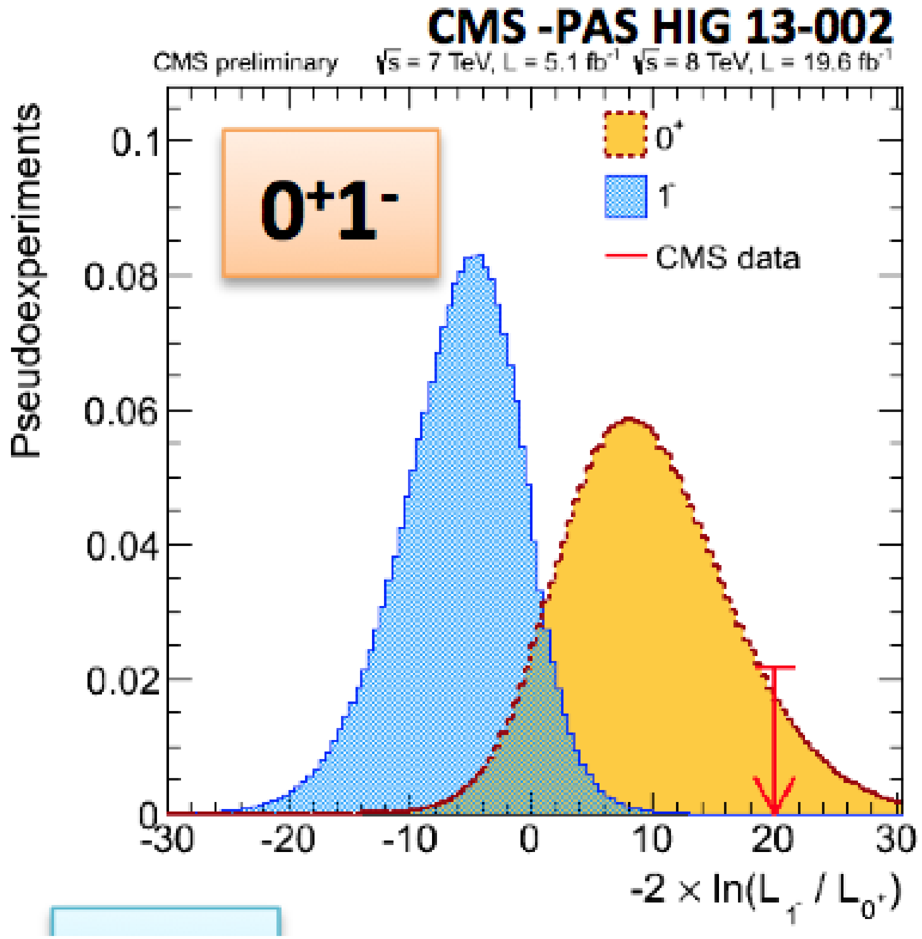
Present data already favour 0^{++}

For example

$H \to ZZ^* \to 4l$

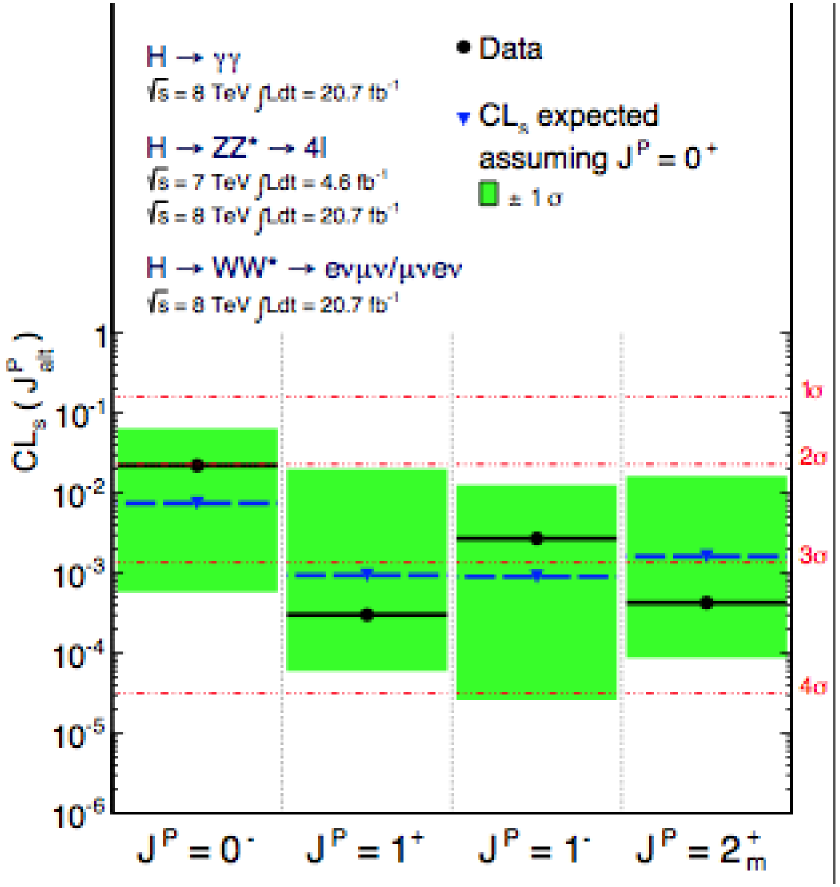
- Data prefers $J^P=0^+$
- $J^P = 0^-, 1^+, 1^-, 2^+_{mgg}, 2^+_{mqq}$ excluded at >95% CL





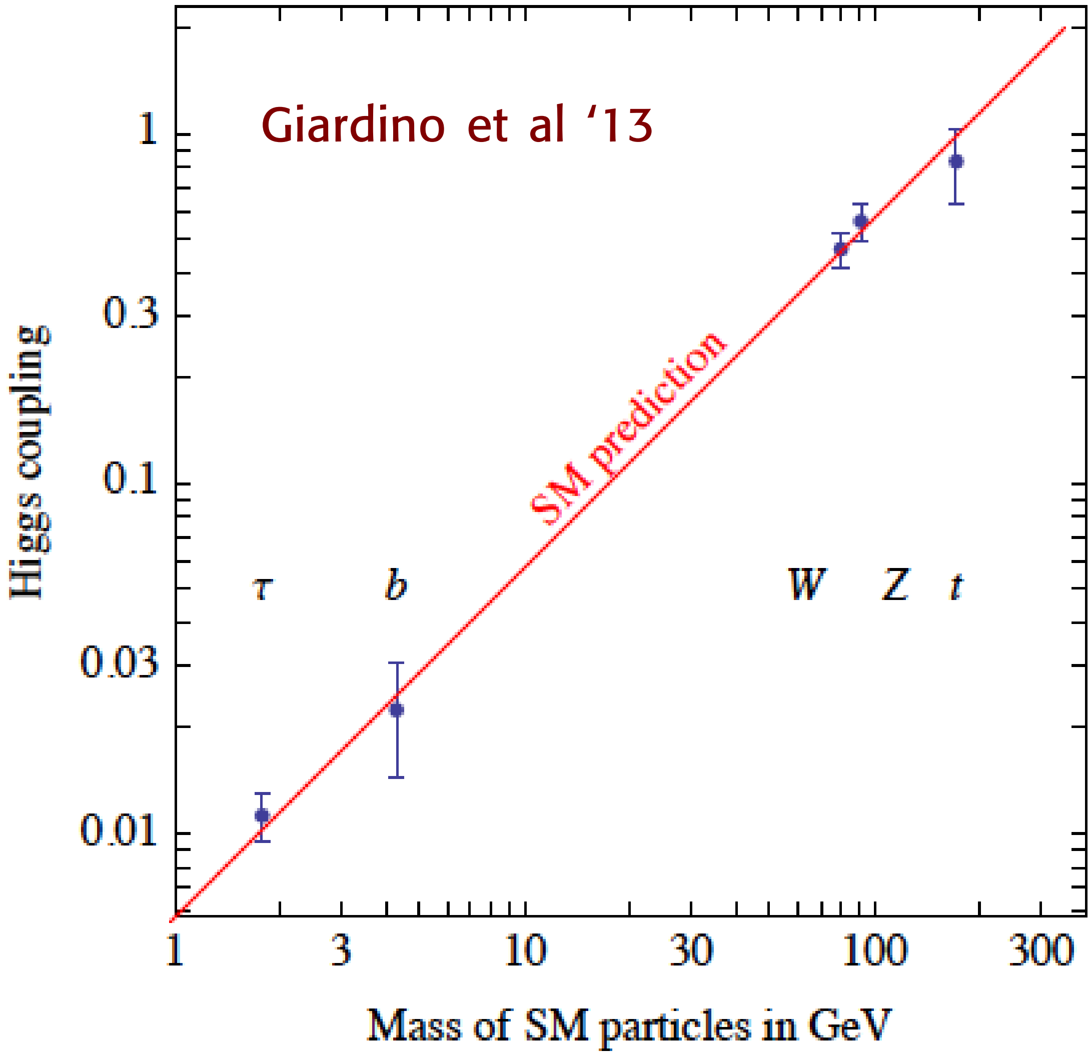
ATLAS

Explored
non SM
J^P assignments
disfavoured



The Higgs couplings are in proportion to masses:
a striking signature [plus specified, gg, γγ, Zγ couplings]

Couplings now
checked at ~20%

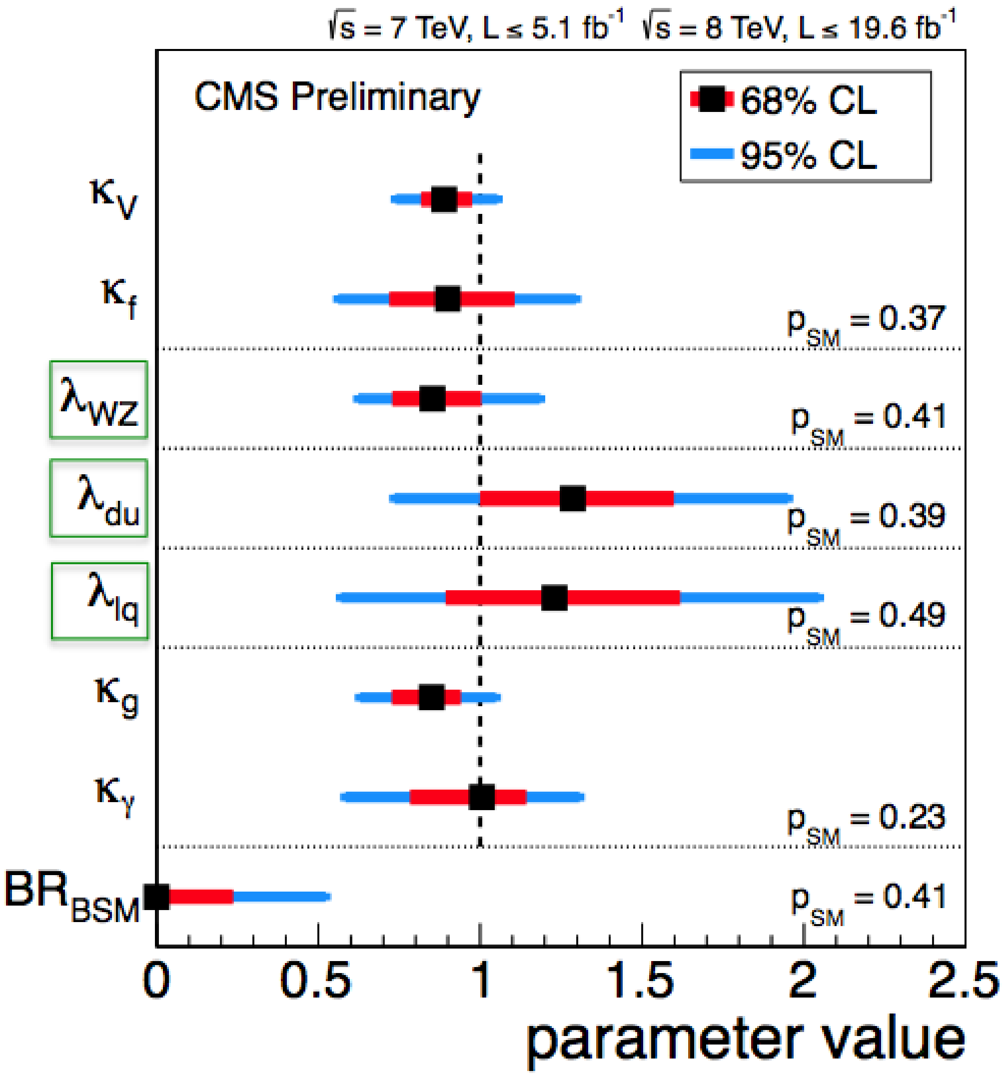


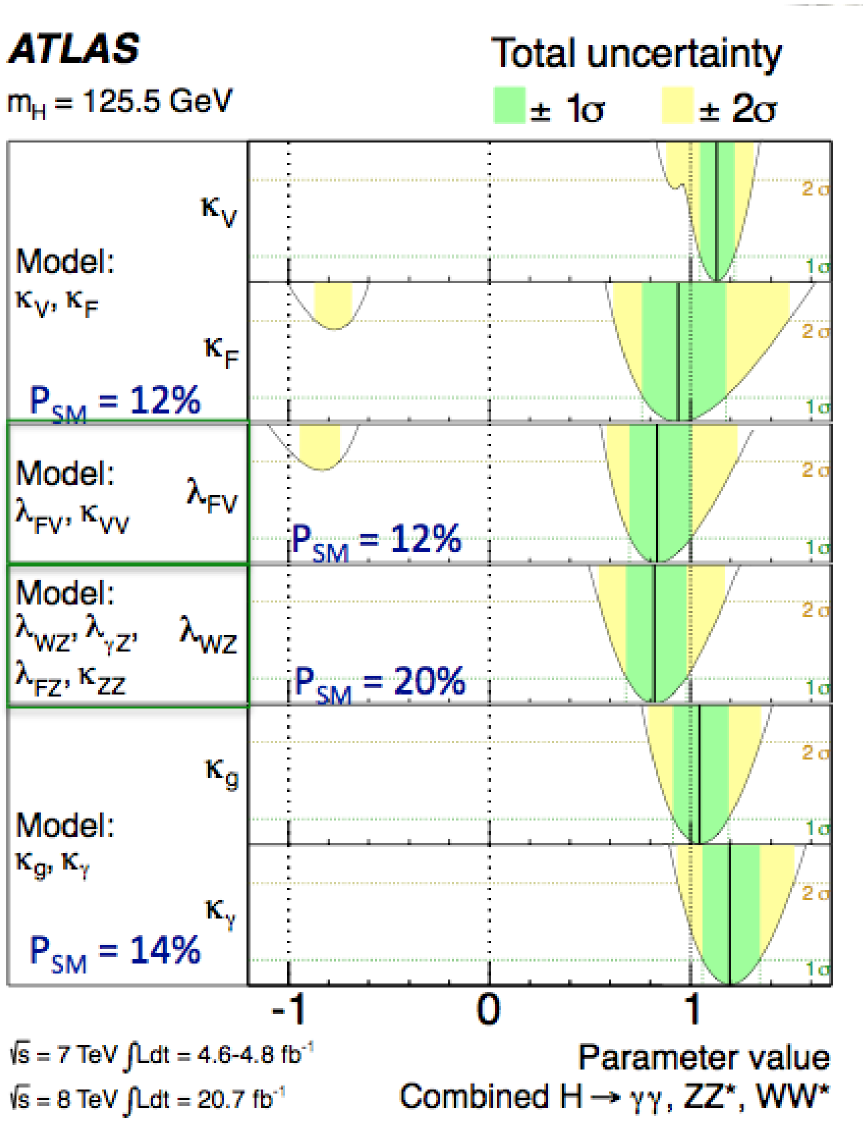
[this is also true
for a dilaton-like,
but up to a
common factor]

Nearly impossible
to reproduce
by accident

Agrees with a SM
doublet: no Clebsch
or mixing distortions

The observed σBr match the predictions within the present accuracy   If not the SM Higgs a very close relative!!





The precise measurements of Higgs couplings are crucial in order to determine to what extent it is SM

It would really be astonishing if no deviation from the SM is seen!

General effective lagrangians are being studied

Gonzalez-Fraile
Falkowski

But within the present limited statistics it is usual to introduce a universal rescaling of couplings to fermions or to VV=WW,ZZ

Contino

$$\mathcal{L} = \frac{1}{2}(\partial_\mu h)^2 - \frac{1}{2}m_h^2 h^2 - \frac{d_3}{6}\left(\frac{3m_h^2}{v}\right)h^3 - \frac{d_4}{24}\left(\frac{3m_h^2}{v^2}\right)h^4 \ldots$$

$$- \left(m_W^2 W_\mu W_\mu + \frac{1}{2}m_Z^2 Z_\mu Z_\mu\right)\left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + \ldots\right)$$

$$- \sum_{\psi=u,d,l} m_{\psi^{(i)}}\bar{\psi}^{(i)}\psi^{(i)}\left(1 + c_\psi\frac{h}{v} + c_{2\psi}\frac{h^2}{v^2} + \ldots\right) + \ldots$$

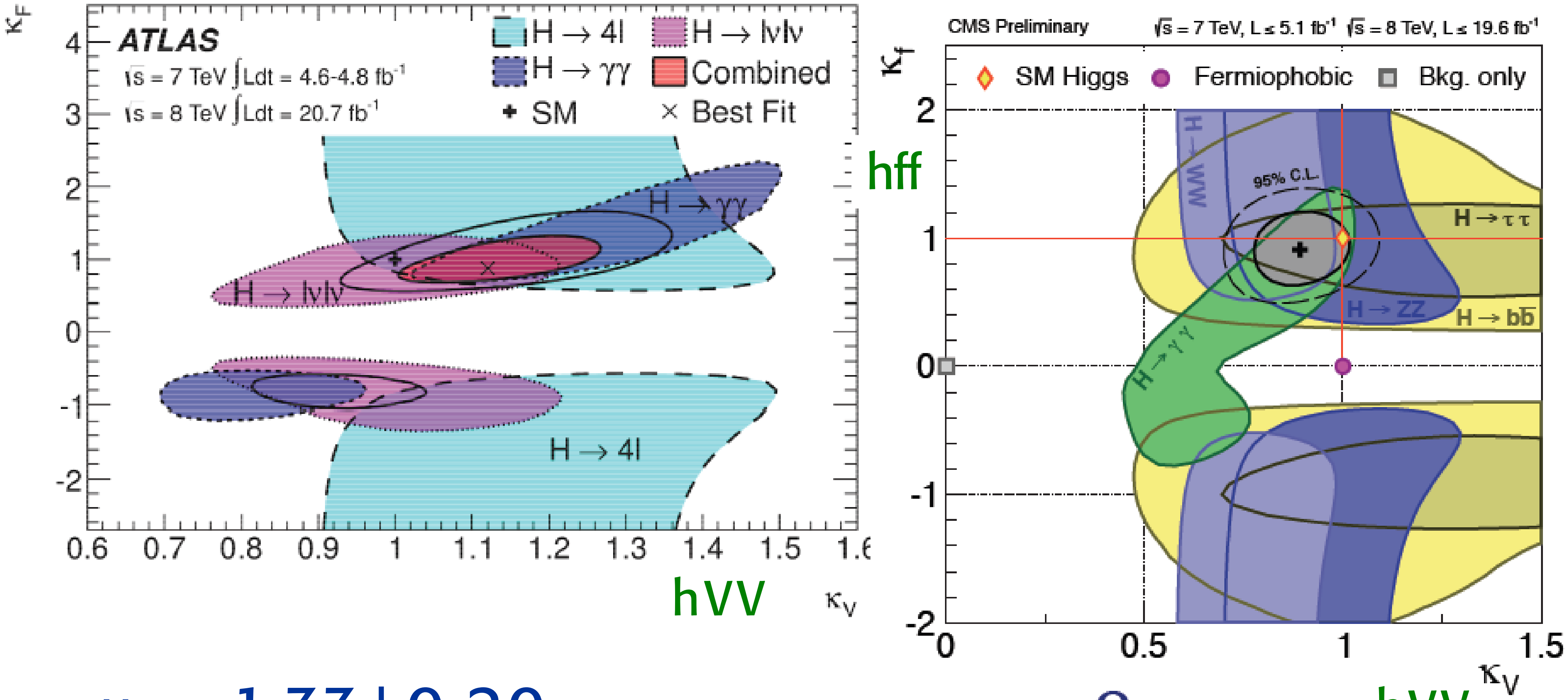
a ~ hVV
c ~ hff

SM:
$a = c = 1$

A long list of References

D. Carmi, A. Falkowski, E. Kuflik and T. Volansky, arXiv:1202.3144. A. Azatov, R. Contino and J. Galloway, arXiv:1202.3415. J. R. Espinosa, C. Grojean, M. Muhlleitner and M. Trott, arXiv:1202.3697. T. Li, X. Wan, Y. Wang and S. Zhu, arXiv:1203.5083. J. Ellis and T. You, arXiv:1204.0464. A. Azatov, R. Contino, D. Del Re, J. Galloway, M. Grassi and S. Rahatlou, JHEP 1206 (2012) 134 [arXiv:1204.4817]. M. Klute, R. Lafaye, T. Plehn, M. Rauch and D. Zerwas, arXiv:1205.2699; A. Azatov, S. Chang, N. Craig and J. Galloway, Phys. Rev. D 86 (2012) 075033 [arXiv:1206.1058]. I. Low, J. Lykken and G. Shaughnessy, Phys. Rev. D 86 (2012) 093012 [arXiv:1207.1093]. T. Corbett, O. J. P. Eboli, J. Gonzalez-Fraile and M. C. Gonzalez-Garcia, Phys. Rev. D 86 (2012) 075013 [arXiv:1207.1344]. M. R. Buckley and D. Hooper, Phys. Rev. D 86 (2012) 075008 [arXiv:1207.1445]. M. Montull and F. Riva, JHEP 1211 (2012) 018 [arXiv:1207.1716]. J. R. Espinosa, C. Grojean, M. Muhlleitner and M. Trott, arXiv:1207.1717. D. Carmi, A. Falkowski, E. Kuflik, T. Volansky and J. Zupan, JHEP 1210 (2012) 196 [arXiv:1207.1718]. S. Banerjee, S. Mukhopadhyay and B. Mukhopadhyaya, JHEP 1210 (2012) 062 [arXiv:1207.3588]. D. Bertolini and M. McCullough, JHEP 1212 (2012) 118 [arXiv:1207.4209]. F. Bonnet, T. Ota, M. Rauch and W. Winter, Phys. Rev. D 86 (2012) 093014 [arXiv:1207.4599]. T. Plehn and M. Rauch, Europhys. Lett. 100 (2012) 11002 [arXiv:1207.6108]. J. R. Espinosa, C. Grojean, V. Sanz and M. Trott, arXiv:1207.7355. A. Djouadi, arXiv:1208.3436. G. Cacciapaglia, A. Deandrea, G. D. La Rochelle and J. -B. Flament, arXiv:1210.8120. G. Moreau, arXiv:1210.3977. G. Belanger, B. Dumont, U. Ellwanger, J. F. Gunion and S. Kraml, JHEP 1302 (2013) 053 E. Masso and V. Sanz, arXiv:1211.1320. T. Corbett, O. J. P. Eboli, J. Gonzalez-Fraile and M. C. Gonzalez-Garcia, Phys. Rev. D 87 (2013) 015022 [arXiv:1211.4580]. [arXiv:1212.5244]. C. Cheung, S. D. McDermott and K. M. Zurek, arXiv:1302.0314. K. Cheung, J. S. Lee and P. -Y. Tseng, arXiv:1302.3794. A. Falkowski, F. Riva and A. Urbano, arXiv:1303.1812.

Each experiment fits the couplings from their data



$\mu = 1.33 \pm 0.20$

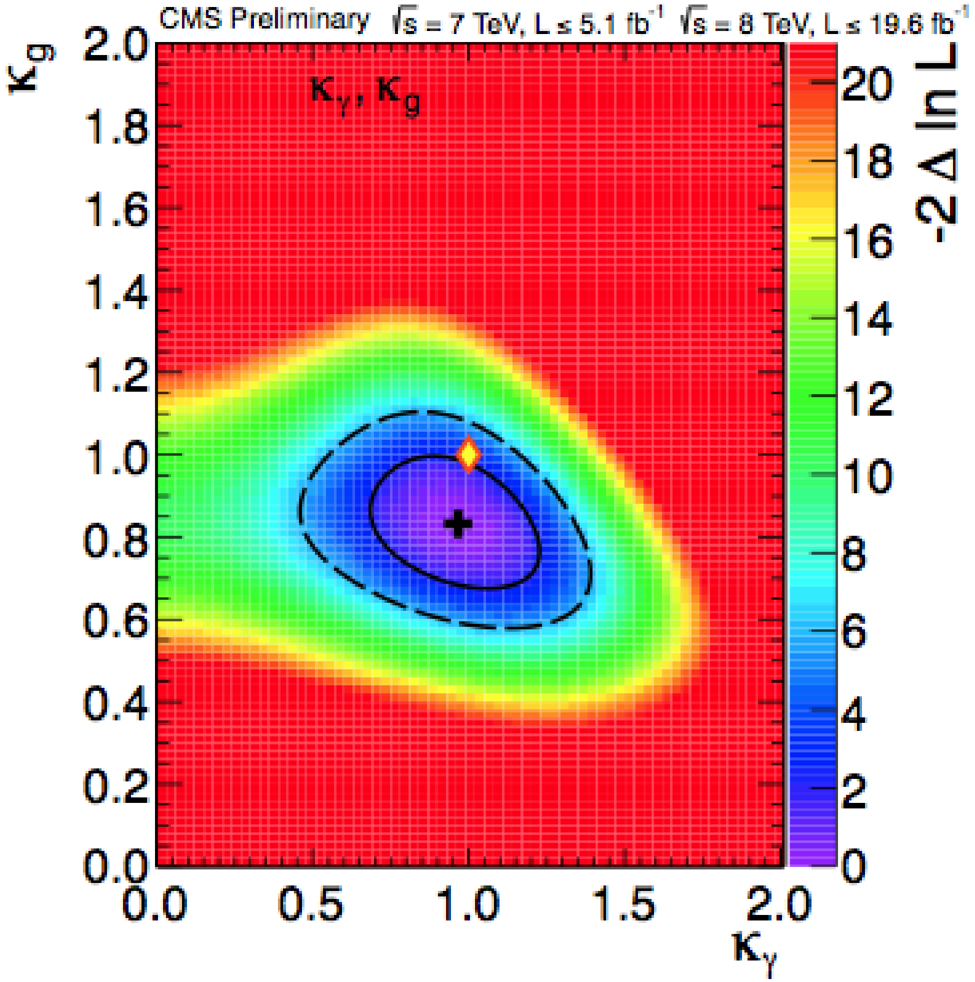
$\mu = 0.80 \pm 0.14$

μ = observed signal/SM prediction

New Physics in loops?

$$\Delta L = r_\gamma c^{\gamma\gamma}_{SM} \frac{\alpha}{\pi V} h F_{\mu\nu} F_{\mu\nu} + r_g c^{gg}_{SM} \frac{\alpha_s}{12\pi V} h G^a_{\mu\nu} G^a_{\mu\nu}$$

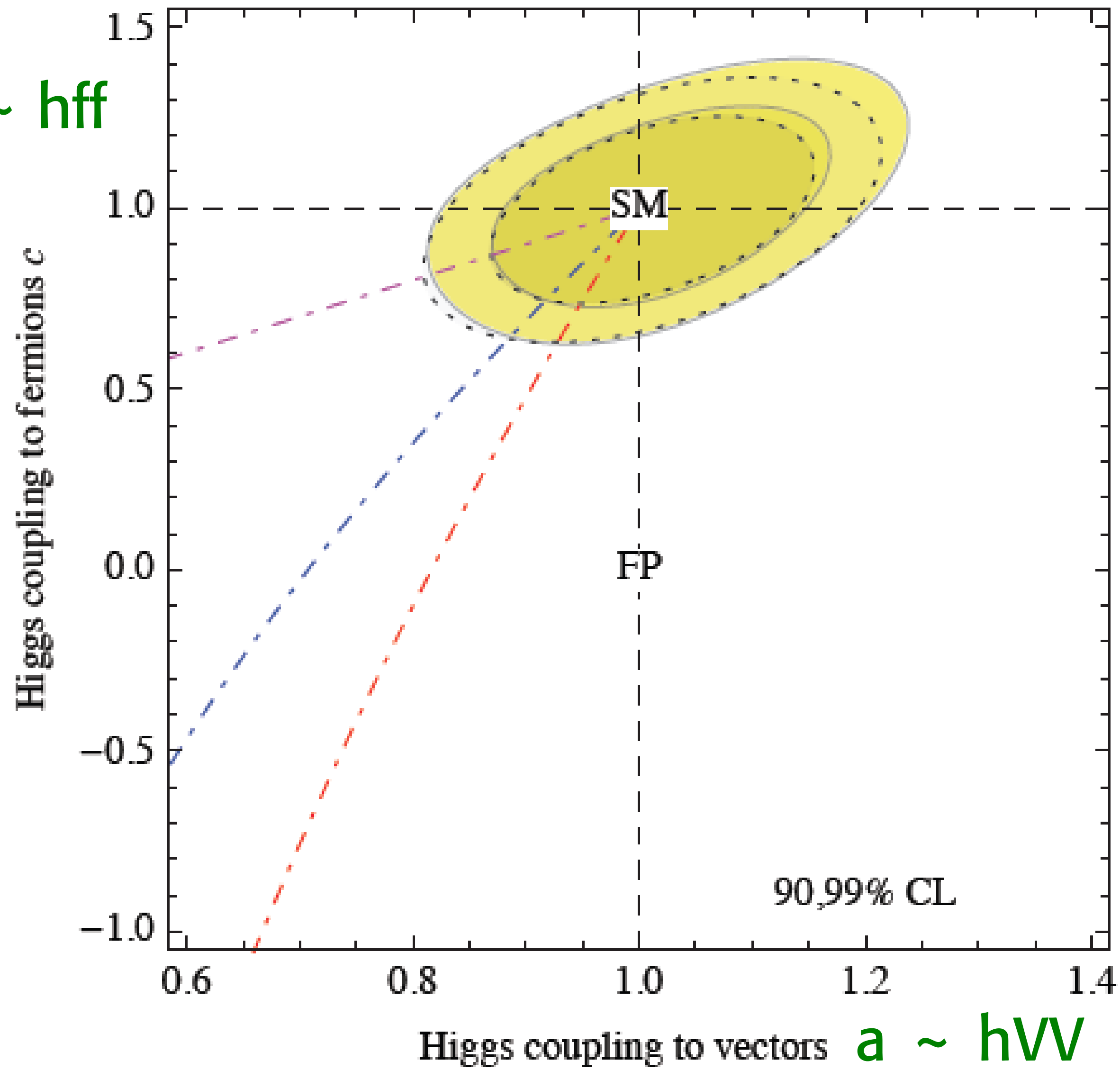
CMS



Theorists informal and abusive combination of ATLAS&CMS data

Giardino et al '13

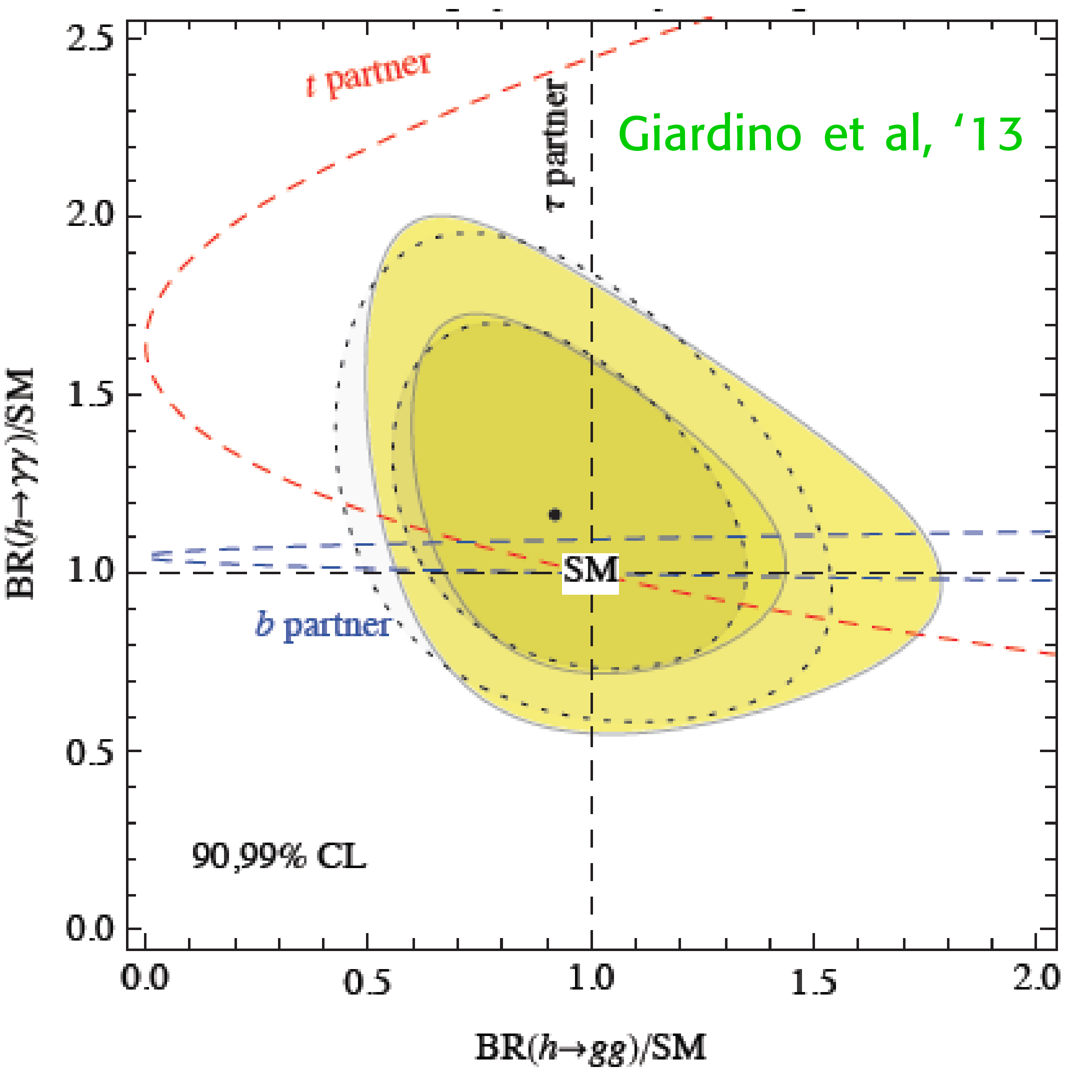
c ~ hff



a ~ hVV

New Physics in loops?

$$\Delta L = r_\gamma c_{SM}^{\gamma\gamma} \frac{\alpha}{\pi V} h F_{\mu\nu} F_{\mu\nu} + r_g c_{SM}^{gg} \frac{\alpha_s}{12\pi V} h G^a_{\mu\nu} G^a_{\mu\nu}$$



A 7 parameter fit from a more general effective lagrangian

Falkowski

$$c_V = 1.04^{+0.03}_{-0.03}$$

$$c_u = 0.55^{+0.66}_{-1.72}$$

$$c_d = 1.03^{+0.26}_{-0.20}$$

$$c_l = 1.04^{+0.21}_{-0.21}$$

$$c_{gg} = 0.005^{+0.022}_{-0.031}$$

$$c_{\gamma\gamma} = 0.0001^{+0.0018}_{-0.0021}$$

$$c_{Z\gamma} = 0.006^{+0.015}_{-0.028}$$

$\Delta\chi^2=\chi^2_{SM}$ - χ^2_{min} $=4.9$, with 7 d.o.f.

the SM hypothesis is a perfect fit :-(((

MSSM: separate u and d couplings, | a| < 1

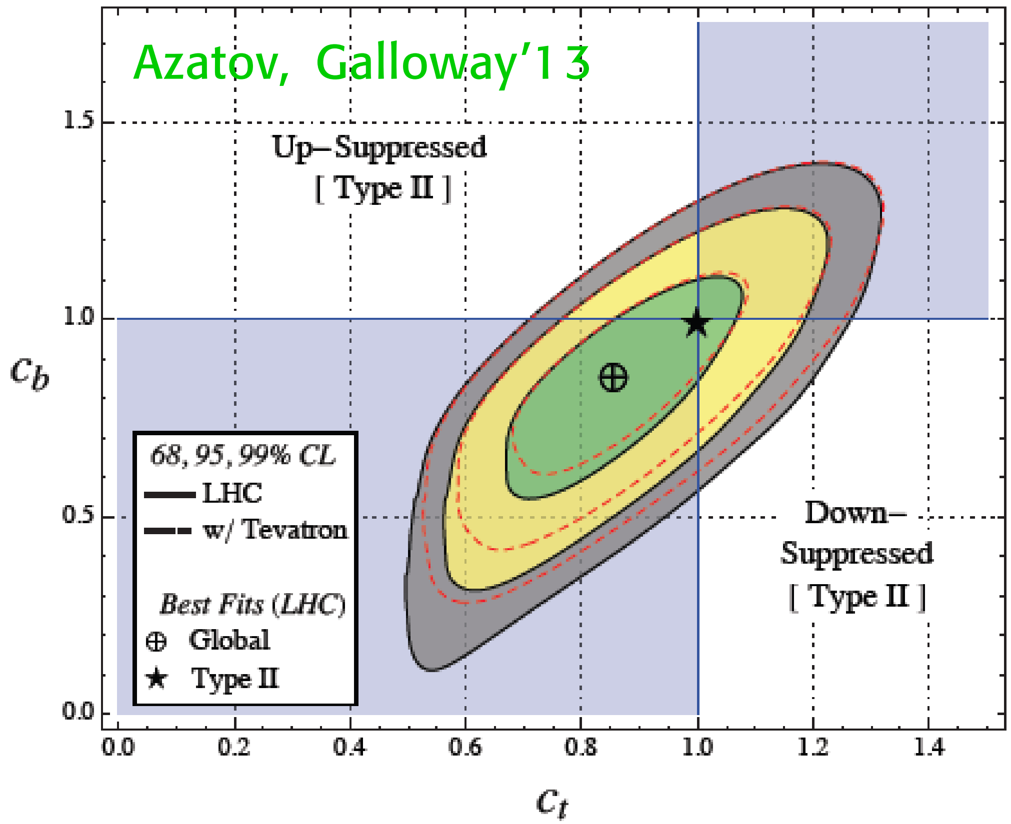
$$a = hVV = \sin(\beta - \alpha)$$

$$c_u = huu = \frac{\cos\alpha}{\sin\beta}$$

$$c_d = hdd = -\frac{\sin\alpha}{\cos\beta}$$

$$\tan 2\alpha = \tan 2\beta \frac{m_A^2 - m_Z^2}{m_A^2 + m_Z^2}$$

If $c_u > 1$ then $c_d < 1$
and viceversa

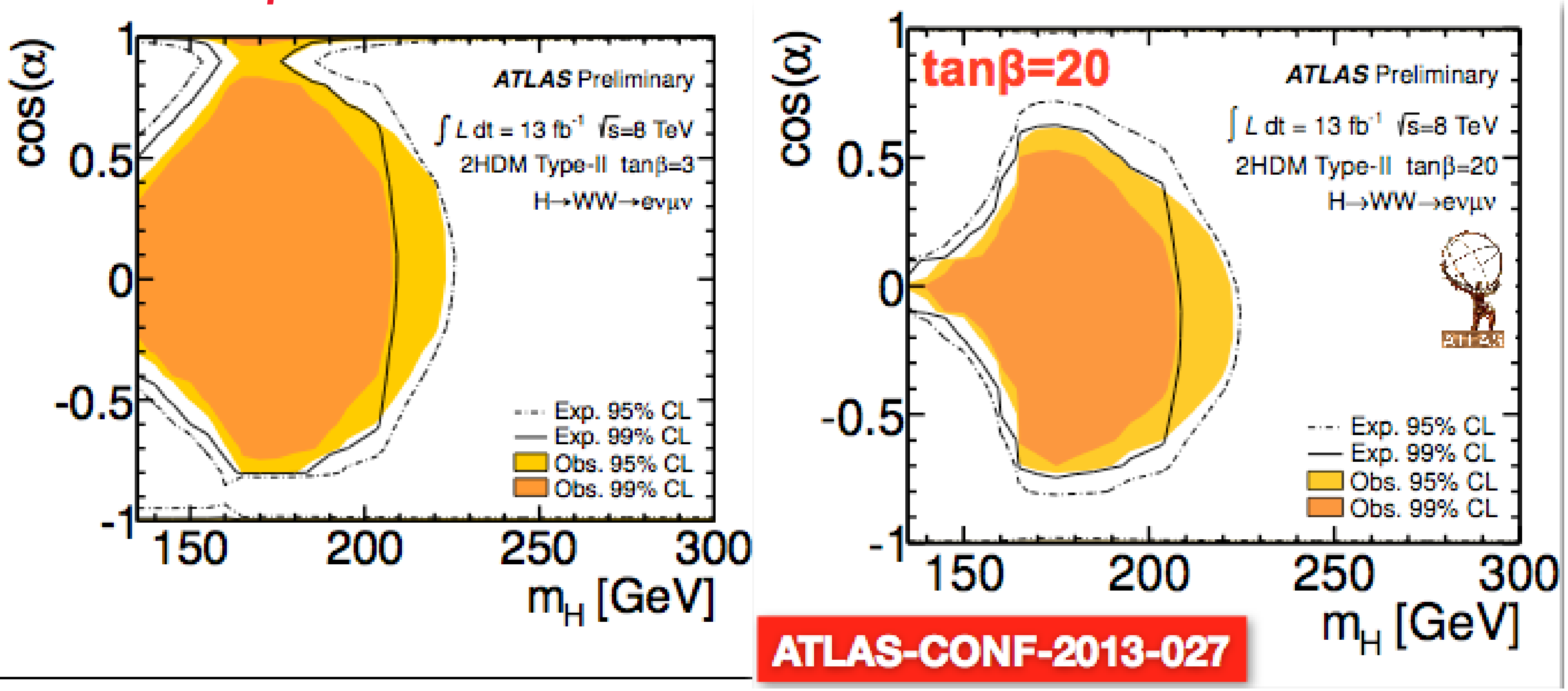


2HDM Type II

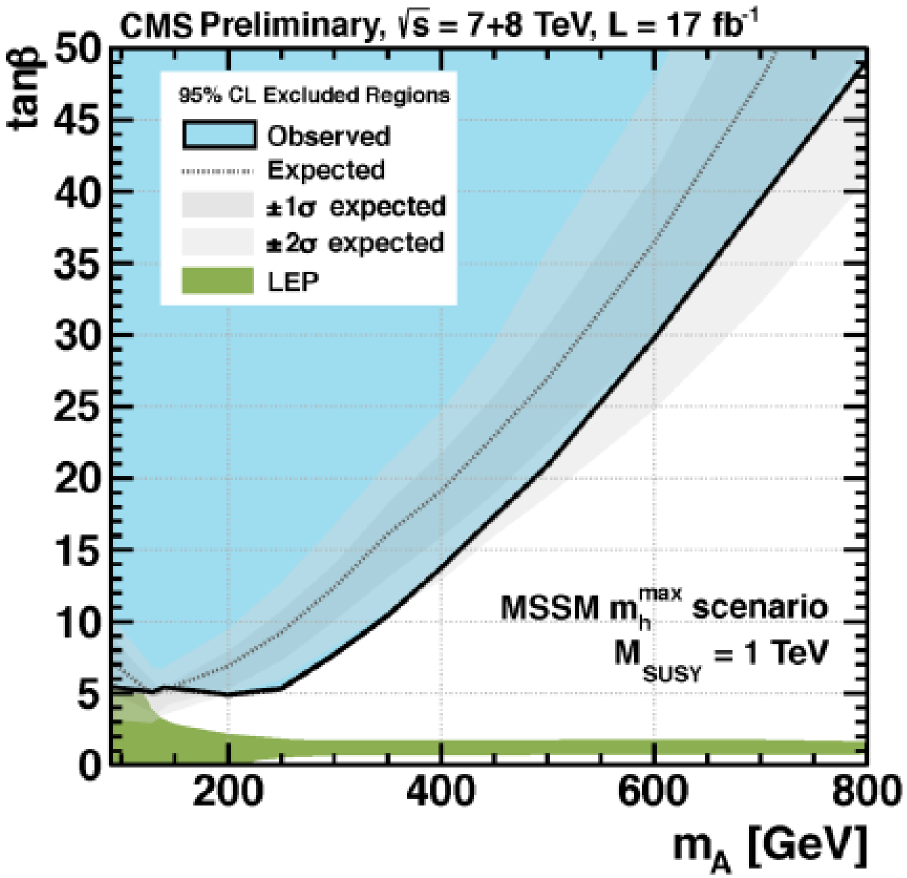
Exclusion contours

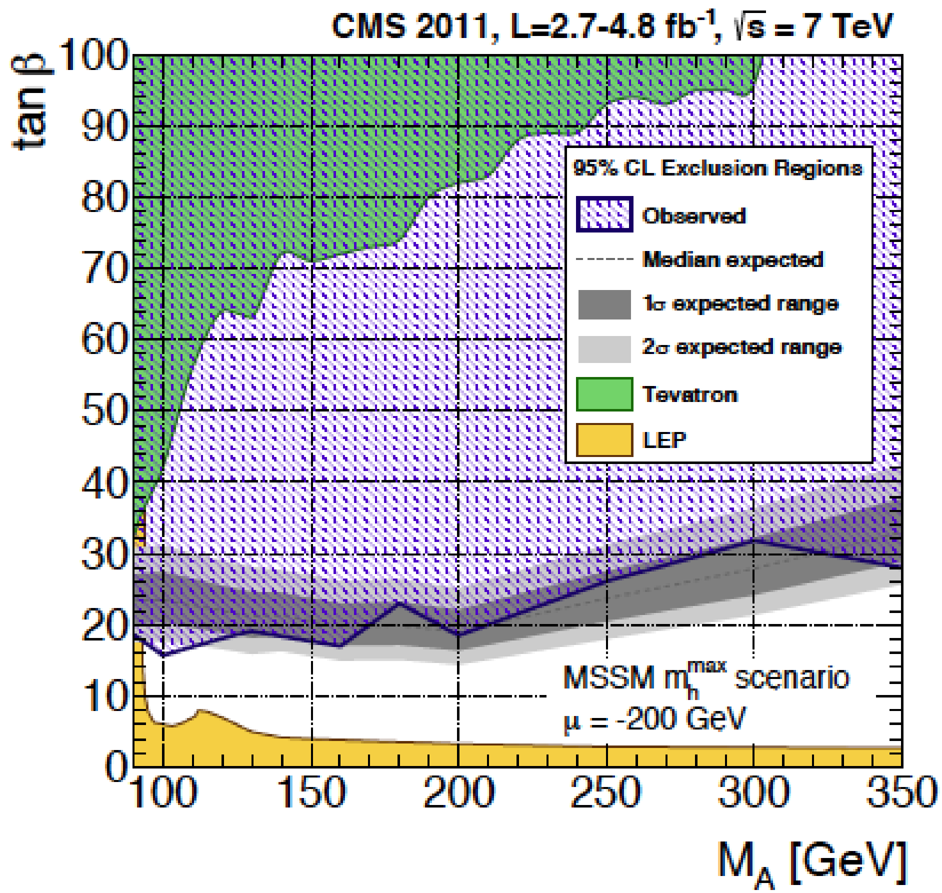
Kaadze
Haber

tanβ=3



Are there more Higgs particles? Focus on MSSM





ττ

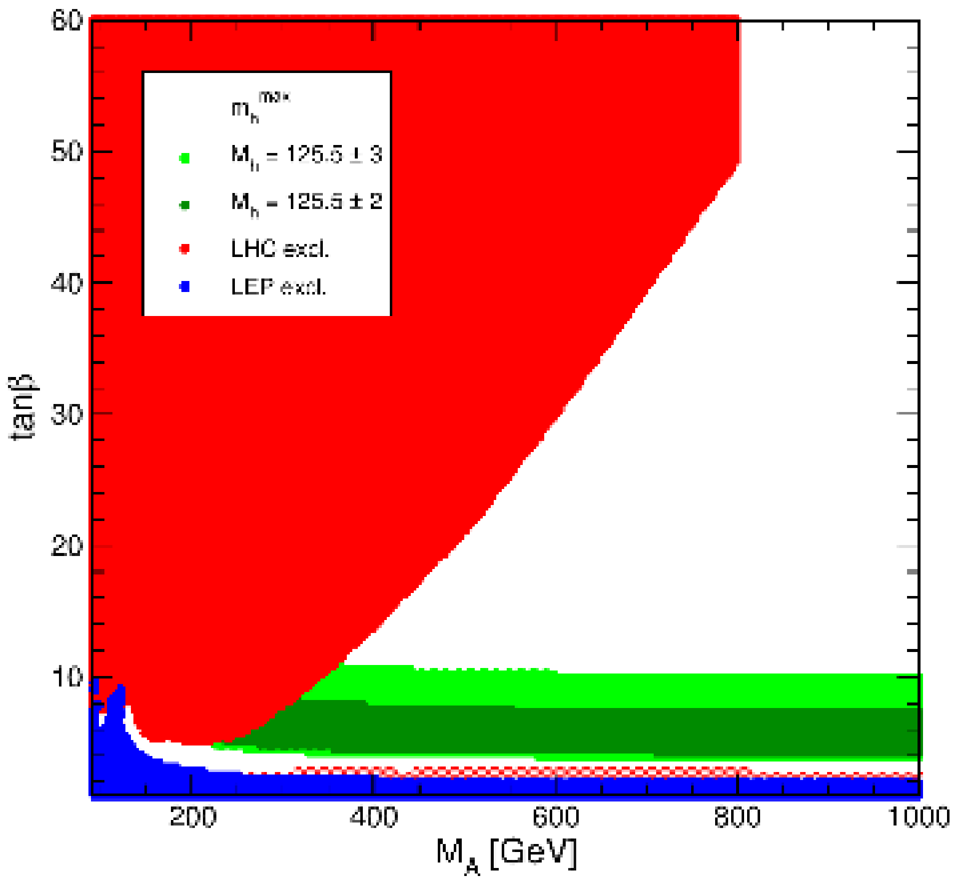
bb

Bianchini
Tanasijczuk

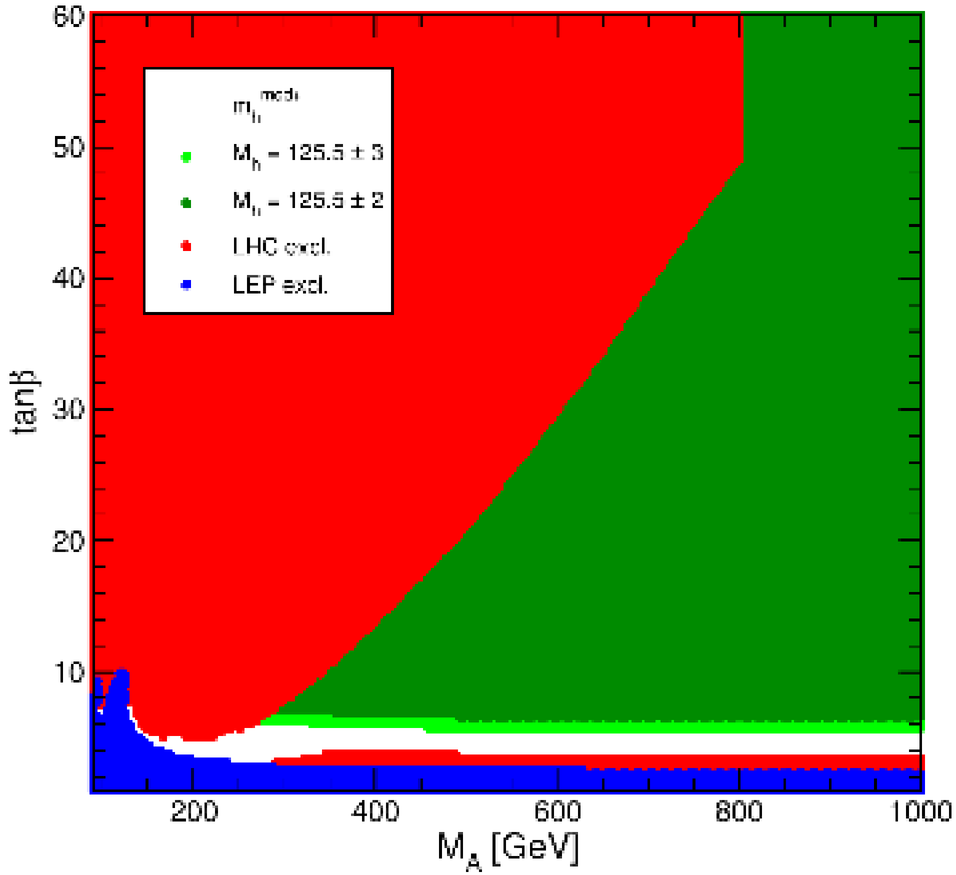
The green region is where the experimental m_h value can be reproduced, depending on the top mixing value X_t

Carena et al 1302.7033

Haber



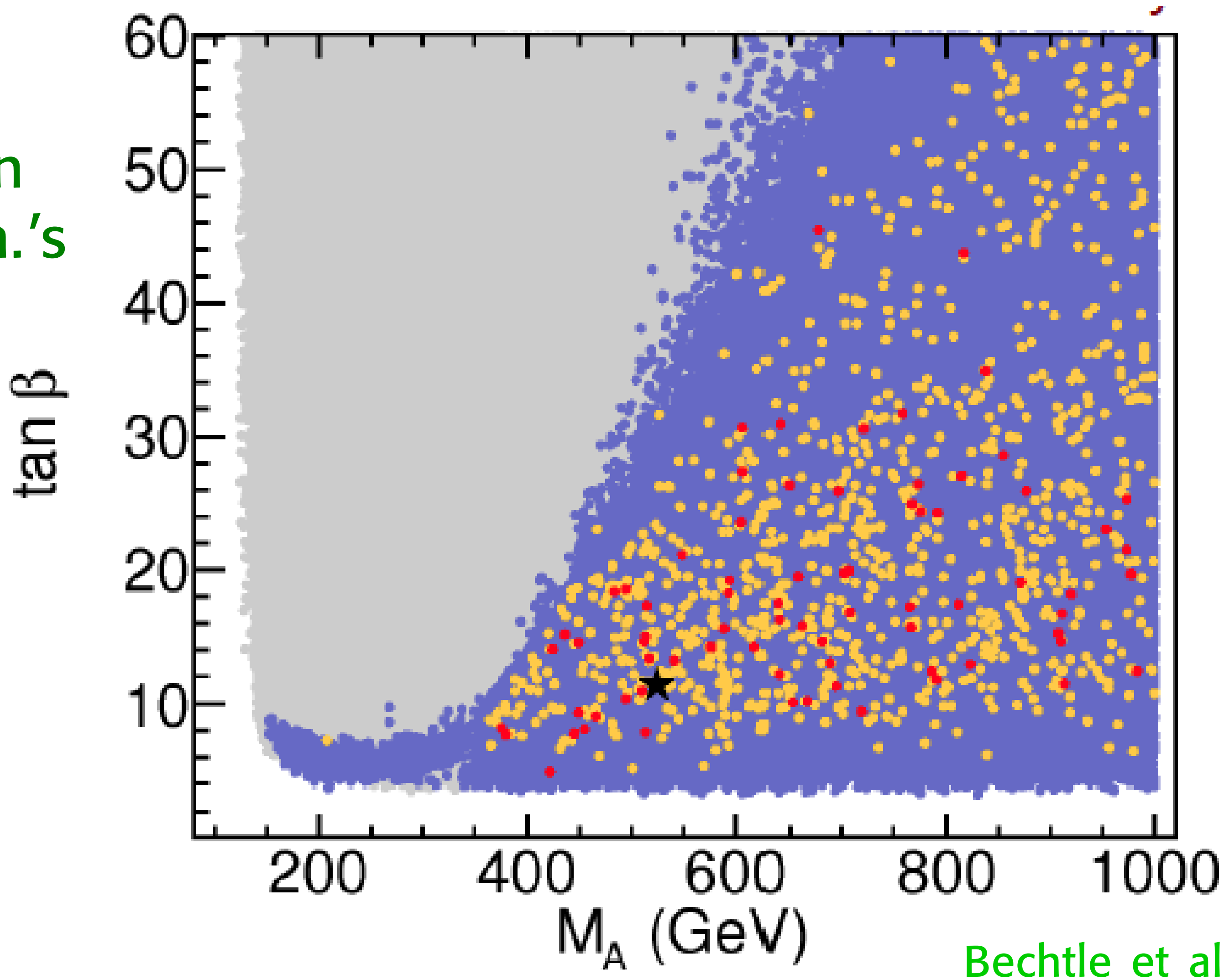
Maximal X_t mixing



Small X_t mixing

Zeune

pMSSM scan
7 (8) param.'s



Bechtle et al

- $(g_\mu - 2)$ differs by more than 3 σ

see also the recent paper Djouadi et al '13

Impact of the Higgs discovery

The minimal SM Higgs:

the simplest possible form of spont. EW symmetry breaking.

What was considered just as a toy model,
a temporary addendum to the gauge part of the SM,
is now promoted to the real thing!

The only known example in physics of a fundamental,
weakly coupled, scalar particle with VEV

$$\lambda|H|^4 \qquad v = 246 GeV \qquad \to \lambda = 0.12$$

A death blow not only to Higgsless models, technicolor models.... but also a threat to all models with no fast enough decoupling

[If new physics comes in a model with decoupling the absence of new particles at the LHC implies small corrections to the H couplings]

The absence of accompanying new physics puts the issue of the relevance of our concept of naturalness at the forefront

Higgs, unitarity and naturalness in the SM

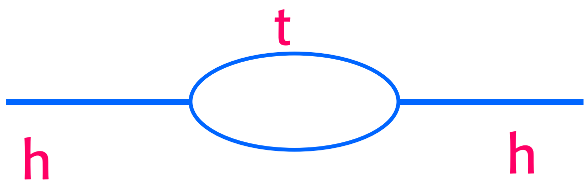
In the SM the Higgs provides a solution to the occurrence of unitarity violations in some amplitudes (W_L, Z_L scattering)

To avoid these violations one needed either one or more Higgs particles or some new states (e.g. new vector bosons)

Something had to happen at the few TeV scale!!

While this is a theorem, once there is the Higgs,
the necessity of new physics on the basis of naturalness
is not a theorem

Higgs light + quadratic divergences ---> cutoff (new physics) nearby



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

The Higgs:

Barbieri

Is it the coronation of the SM or a step on a road still largely unexplored?

2. The reasons for the discontent

$$\mathcal{L}_{ST} = |D_\mu h|^2 - m^2 h^2 - \lambda h^4 + \lambda_{ij} \Psi_i \Psi_j h \ (+\Lambda^4)$$

how natural?

which dynamics, if any?

how about the flavour puzzle?

(Note: no physical inconsistency!)

The SM as an effective theory

With new physics at Λ the low en. th. is an effective theory.

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

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

$$\mathcal{L} = o(\Lambda^4) + o(\Lambda^2)\mathcal{L}_2 + o(\Lambda)\mathcal{L}_3 + o(1)\mathcal{L}_4 + o(1/\Lambda)\mathcal{L}_5 + o(1/\Lambda^2)\mathcal{L}_6 + \ldots$$

Renorm.ble part (terms up to $o(1)\mathcal{L}_4$) — Non renorm.ble part (terms from $o(1/\Lambda)\mathcal{L}_5$ on)

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: $c_2 \sim o(\Lambda^2)$

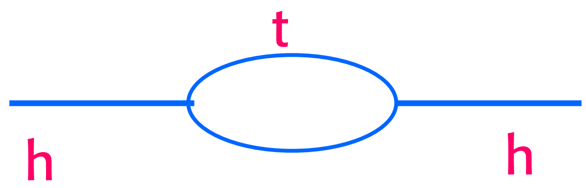
$\mathcal{L}_3$: Fermion masses $\bar{\psi}\psi$. Protected by chiral symmetry and SU(2)xU(1): $\Lambda \rightarrow m\log\Lambda$

$\mathcal{L}_4$: 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 naturalness argument for new physics at the EW scale is not a theorem but a conceptual demand

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



However, it is true that the SM theory is renormalizable.
Thus if one ignores the hierarchy problem it is completely finite and predictive
If you do not care about fine tuning you are not punished!!

Only if we see the cutoff as the scale where new physics occurs that solves the infinities problem, then the strong indication that Λ must be nearby follows

The naturalness principle

Has been and is the main motivation for new physics at the weak scale

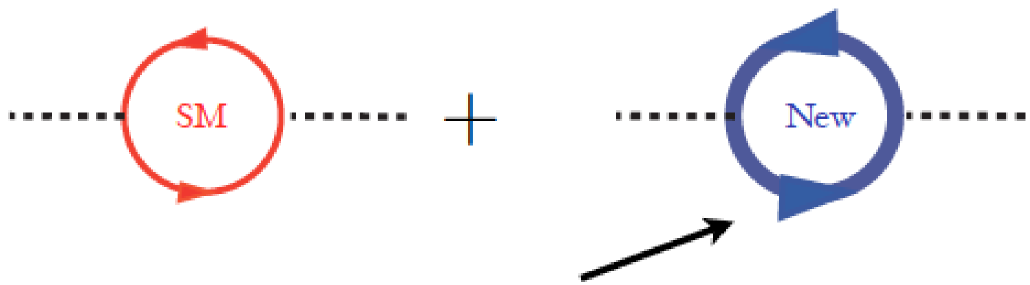
But at present our confidence on naturalness as a guiding principle is being more and more challenged

No indirect evidence of new physics (g-2?)
No direct evidence of new physics at the LHC

Apparently some amount of fine tuning is imposed on us by the data. More now after the LHC7-8 results

Does Nature really care about our concept of Naturalness? Apparently not much!
Which form of Naturalness is Natural?

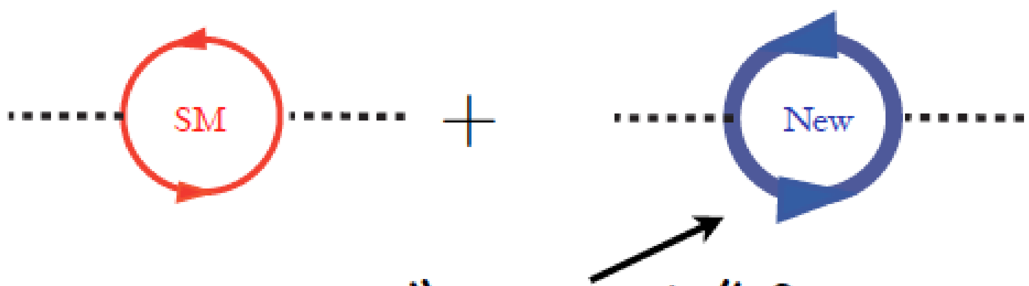
Natural theories **Supersymmetry** Barbieri

$\delta m_H^2 =$  ~ 0

s-particles

The Higgs boson as a pseudoGolsdtone

(like the π in QCD)

$\delta m_H^2 =$  ~ 0

Heavy "composite" fermions

Question: Nothing seen so far. Shouldn't we worry?

$M_{New} \gtrsim 500 \div 1000\ GeV$

COMPOSITE MODELS ARE IN PRINCIPLE DOING WELL FOR THE HIGGS POTENTIAL AND 125 GeV, AS GOOD AS SUPERSYMMETRY

Pokorski

BUT,

A LOT OF ARBITRARINESS ,

NO EASY UV COMPLETIONS

RENORMALISABILITY – NO LONGER AN ISSUE?

- Composite Higgs

Georgi, Kaplan '84; Kaplan '91; Agashe, Contino, Pomarol '05; Agashe et al '06; Giudice et al '07; Contino et al '07; Csaki, Falkowski, Weiler '08; Contino, Servant '08; Mrazek, Wulzer '10; Panico, Wulzer '11; De Curtis, Redi, Tesi '11;Marzocca, Serone, Shu '12; Pomarol, Riva'12; De Simone et al '12.........

The light Higgs is a bound state of a strongly interacting sector and a pseudo-Goldstone boson of an enlarged symmetry. eg. SO(5)/SO(4). Can be set up in a holographic ED context.

v ~ EW scale f ~ SI scale

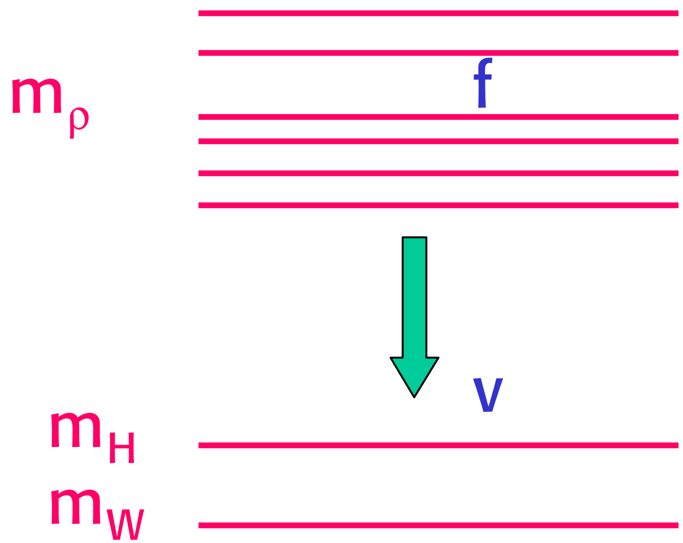
$\sim f < m_\rho <\sim 4\pi f$

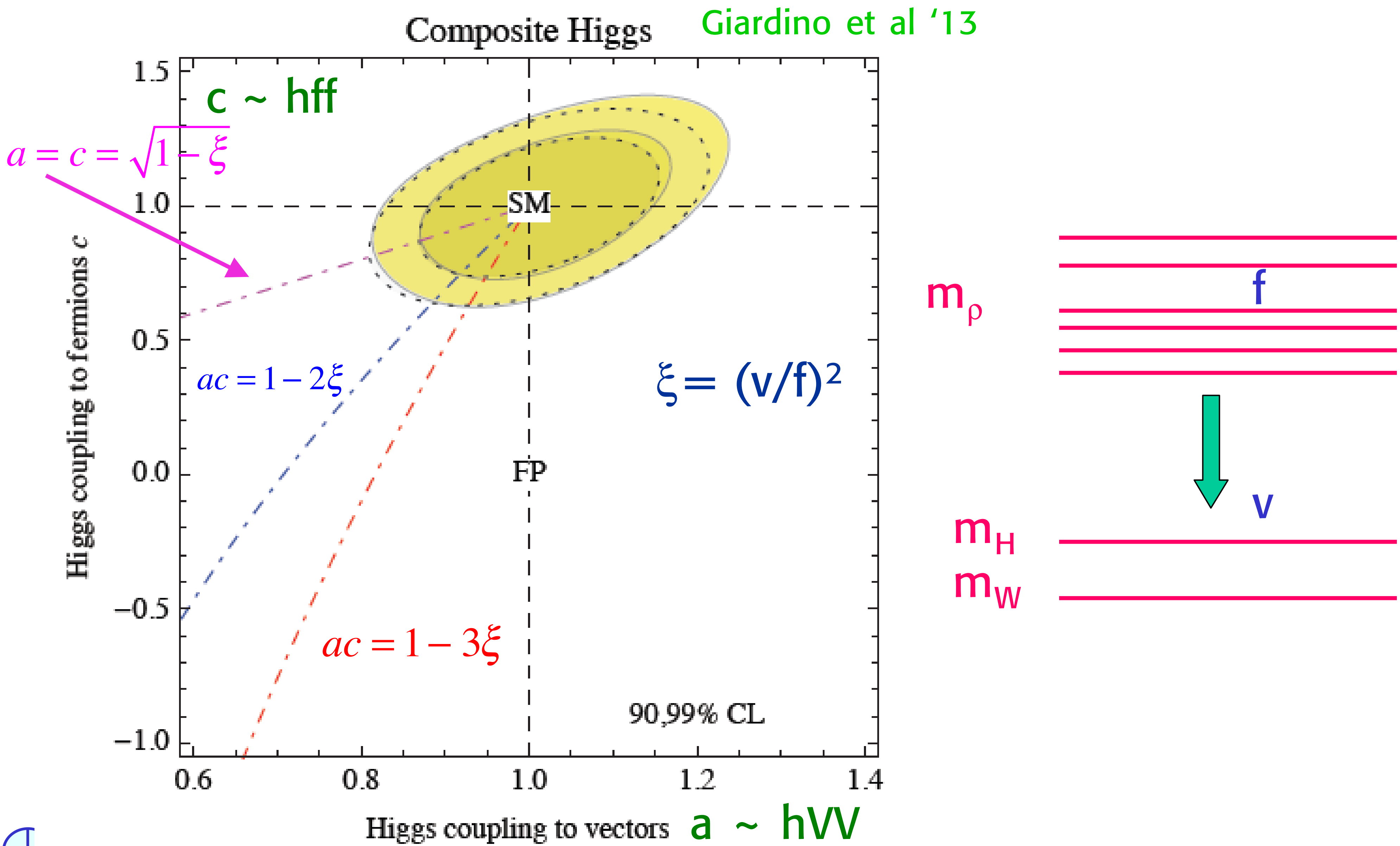
$\xi = (v/f)^2$

ξ interpolates between SM [$\xi \sim 0$] and some degree of compositeness

$\xi \sim 1$ similar to Technicolor

[ξ limited by precision EW tests $\xi < \sim 0.2$]

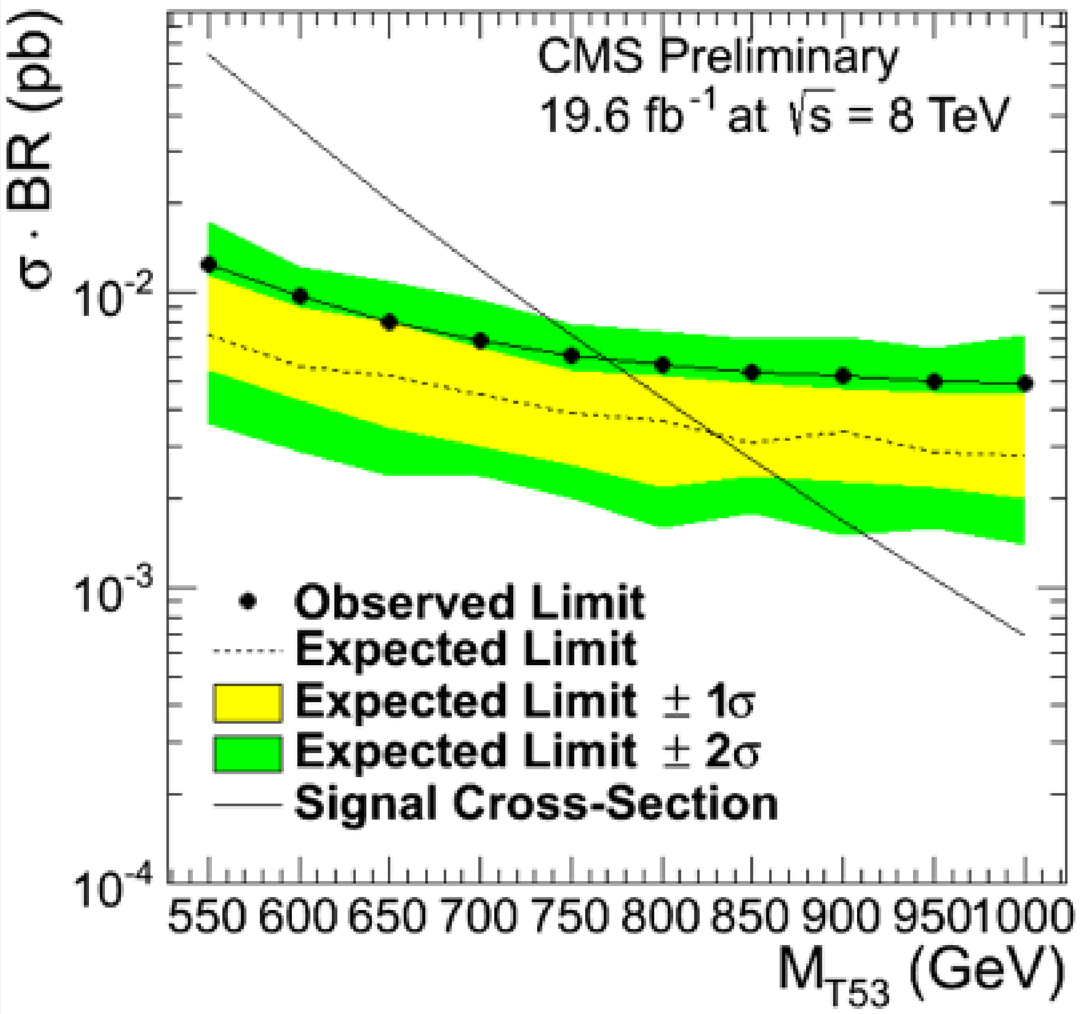




Composite Higgs
Giardino et al '13
c ~ hff
$a = c = \sqrt{1-\xi}$
SM
FP
$ac = 1 - 2\xi$
$ac = 1 - 3\xi$
$\xi = (v/f)^2$
90,99% CL
Higgs coupling to fermions c
Higgs coupling to vectors
a ~ hVV
1.5
1.0
0.5
0.0
−0.5
−1.0
0.6
0.8
1.0
1.2
1.4
m_ρ
f
v
m_H
m_W

Searches for t partners

In composite models the top loop bad behaviour is quenched by a new fermion



Expected and observed 95% C.L. limits on the $T_{5/3}$ production cross section. The 1-sigma and 2-sigma combined statistical and systematic expected variation is shown as a yellow (light) and green (dark) band, respectively.

A 5/3 charged fermion cannot mix and is not pushed up

Two main directions

- "Stealth" Naturalness: build models where naturalness is restored not too far from the weak scale but the related New Physics is arranged to be not visible so far

SUSY

For an orderly retreat simplest new ingredients are

- Heavy first 2 generations
- NMSSM (an extra Higgs singlet)

The last trench of natural SUSY!

Composite Higgs

H as PGB of extended symm.
q and l mix with comp. ferm.

Key role of light top partners

- Large Fine-Tuning models: disregard the naturalness principle in part or even completely and explore possible, viable models (wrt Dark Matter, ν masses, Baryogenesis...)

One must go beyond the simplest versions with few parameters CMSSM, mSUGRA, NUHM1,2

There is plenty of room for more sophisticated versions of SUSY as a solution to the hierarchy problem

For an orderly retreat

Simplest new ingredients

- Heavy first 2 generations, light stops, higgsinos, gluinos
- NMSSM
- λ SUSY

(NMSSM and λ SUSY: an extra Higgs singlet)

The last trench of natural SUSY!

- Natural SUSY

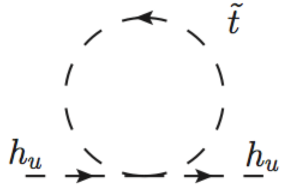
For MSSM to be natural

$m_{\tilde{g}}, m_{\tilde{t}}, m_{\tilde{b}}, m_{\tilde{h}}$ < ~1 TeV

Tree level $\sin^2 2\beta << 1$
(no extra singlet in MSSM)

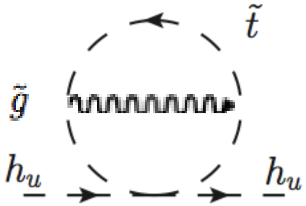
$$-\frac{m_Z^2}{2} = |\mu|^2 + m_{H_u}^2$$

μ related to lightest Higgsino mass



$$\delta m_{H_u}^2|_{stop} = -\frac{3}{8\pi^2} y_t^2 \left(m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2 + |A_t|^2\right) \log\left(\frac{\Lambda}{\mathrm{TeV}}\right)$$

largest radiative corrections
involve s-top and gluinos



$$\delta m_{H_u}^2|_{gluino} = -\frac{2}{\pi^2} y_t^2 \left(\frac{\alpha_s}{\pi}\right) |M_3|^2 \log^2\left(\frac{\Lambda}{\mathrm{TeV}}\right)$$

Beyond the CMSSM, mSugra, NUHM1,2 that are under stress

Heavy 1st, 2nd generations

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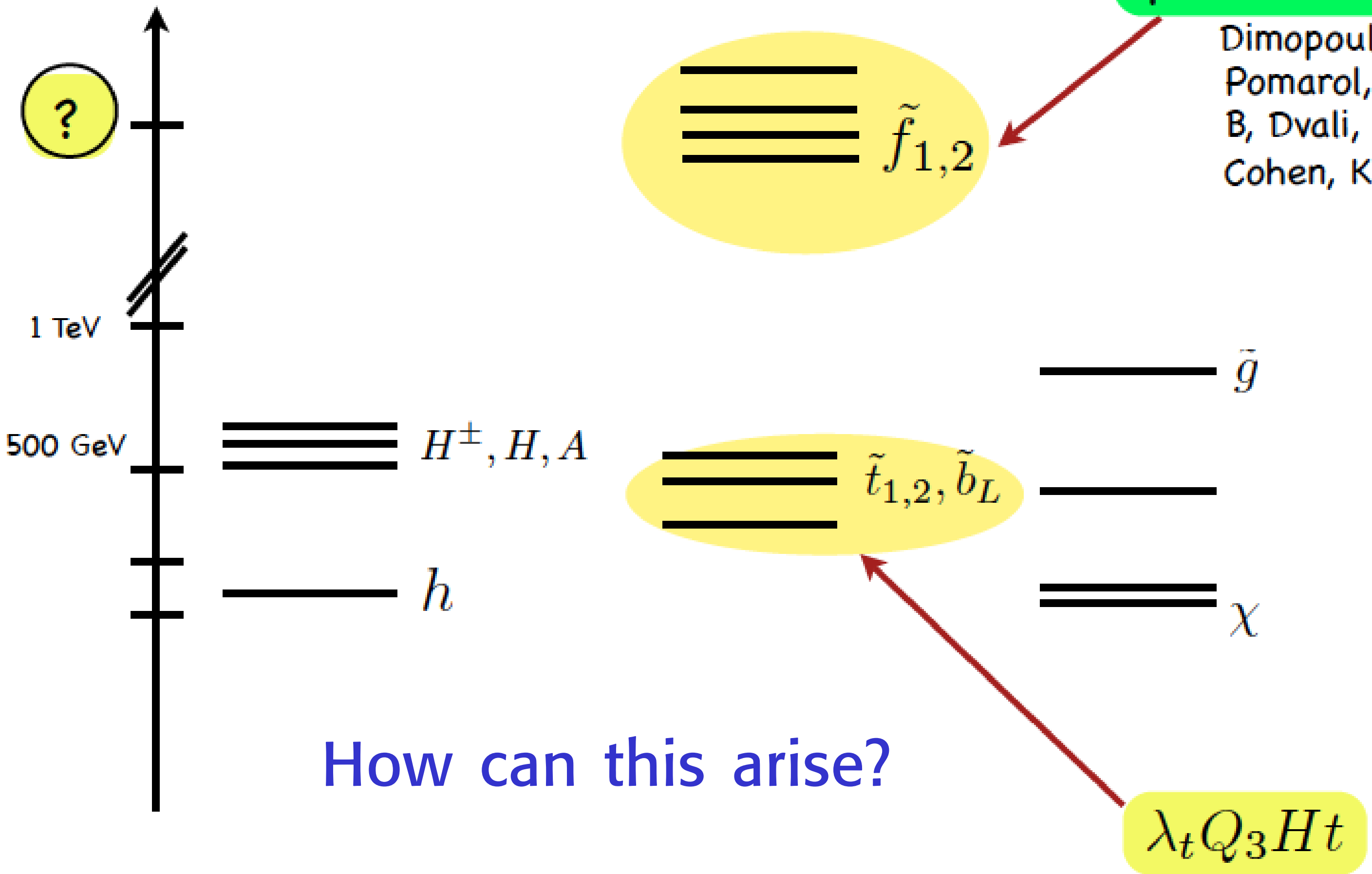

Flavour and CP problems improved

Dimopoulos, Giudice 1995
Pomarol, Tommasini 1995
B, Dvali, Hall 1995
Cohen, Kaplan, Nelson 1996

pioneer papers

recent papers, e.g.

Papucci et al '11
Brust et al '11
Essig et al '11
Katz et al '11
Larsen et al '12
Csaki et al '12
.....

How can this arise?

For g-2
light sleptons
welcome

Going beyond the MSSM: 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)

$\lambda\, S H_u H_d$

additional term

$$m_h^2 = M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + \delta_t^2$$

Mixing with S can modify the Higgs mass and couplings at tree level

Hall et al '11, King et al '12, Barbieri et al '13.....

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

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

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Bertolini
Tesi

It is not excluded that at 126 GeV the second heaviest is seen while the lightest escaped detection at LEP

⊕ b-phobic Higgs Pokorski

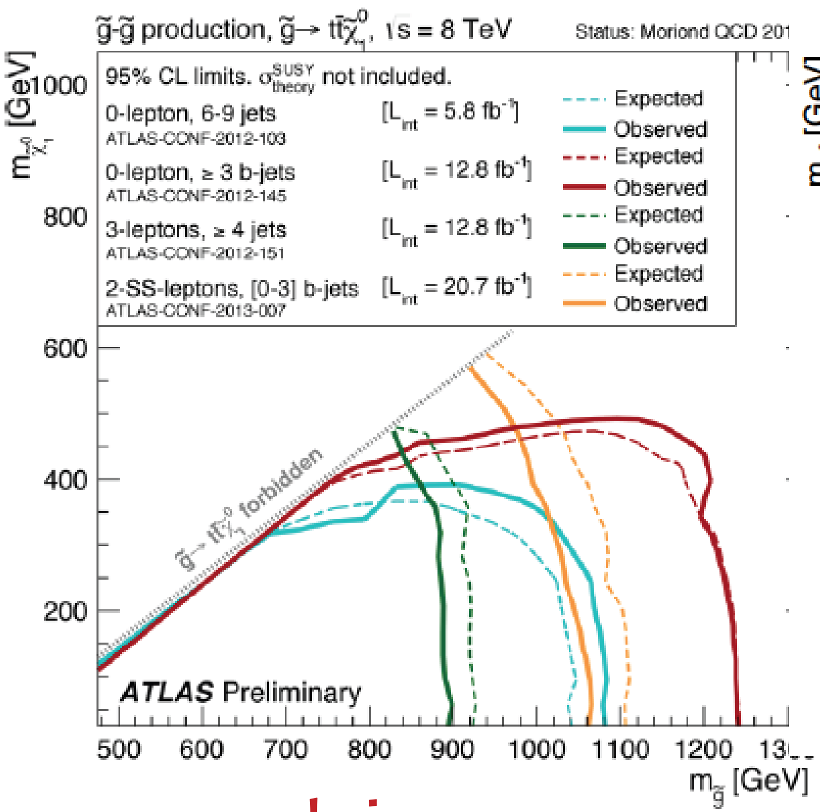
Ellwanger '11, Belanger et al '12

Searches of light gluinos, s-top, s-bottom: already biting hard

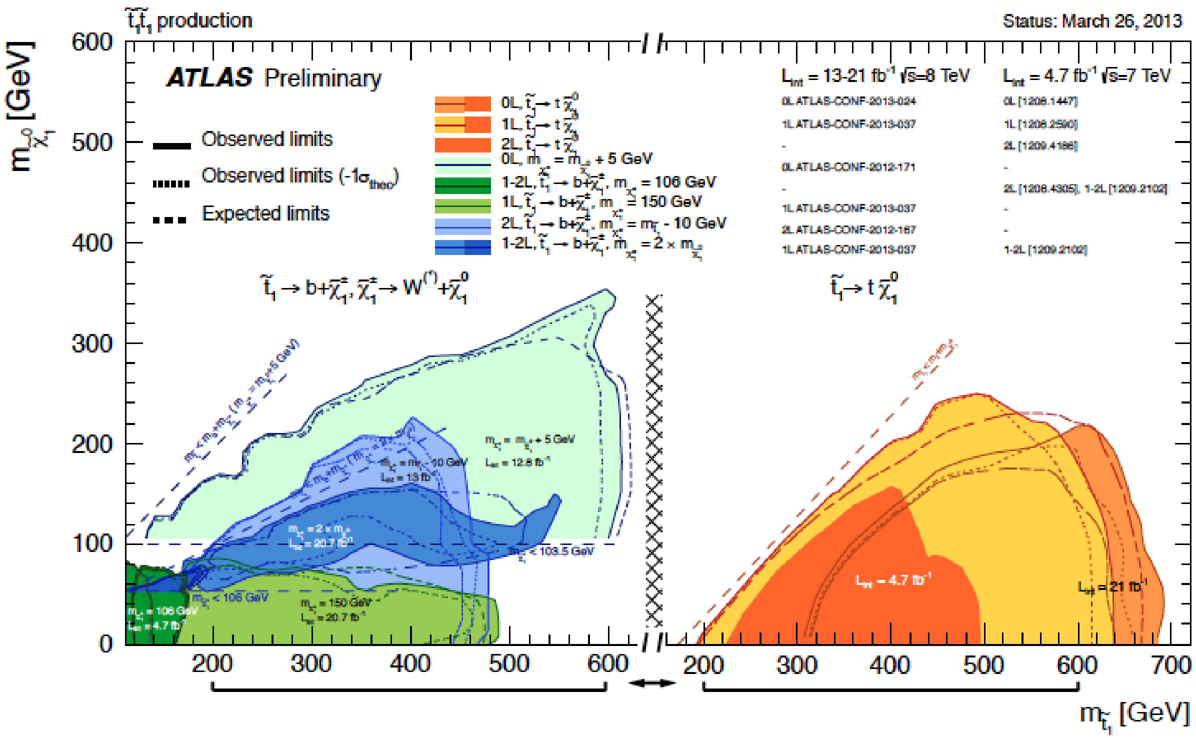
Gluino mediated s-top production: $m_g < 1.2$ TeV excluded under a variety of assumptions

Direct s-top production: $m_{stop} < 0.60\text{-}0.65$ TeV excluded assuming 100% BR for either $b\chi^+$ or $t\chi^0$

ATLAS



gluino

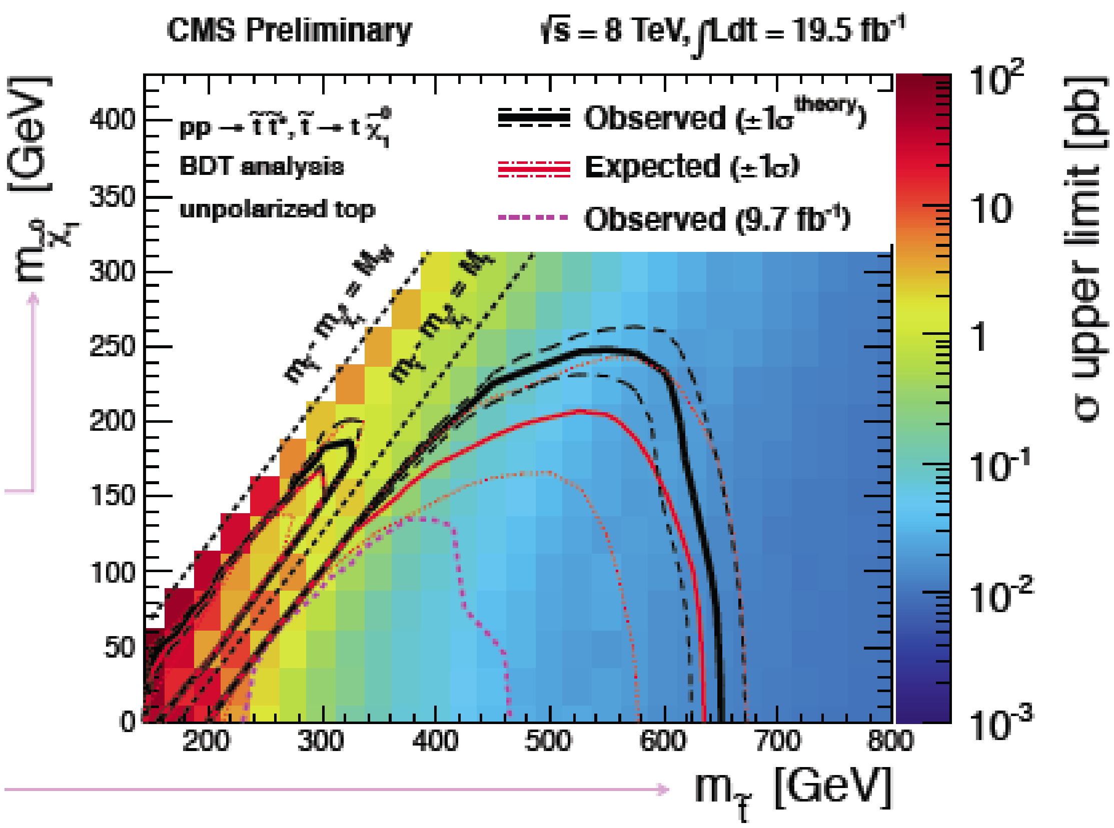


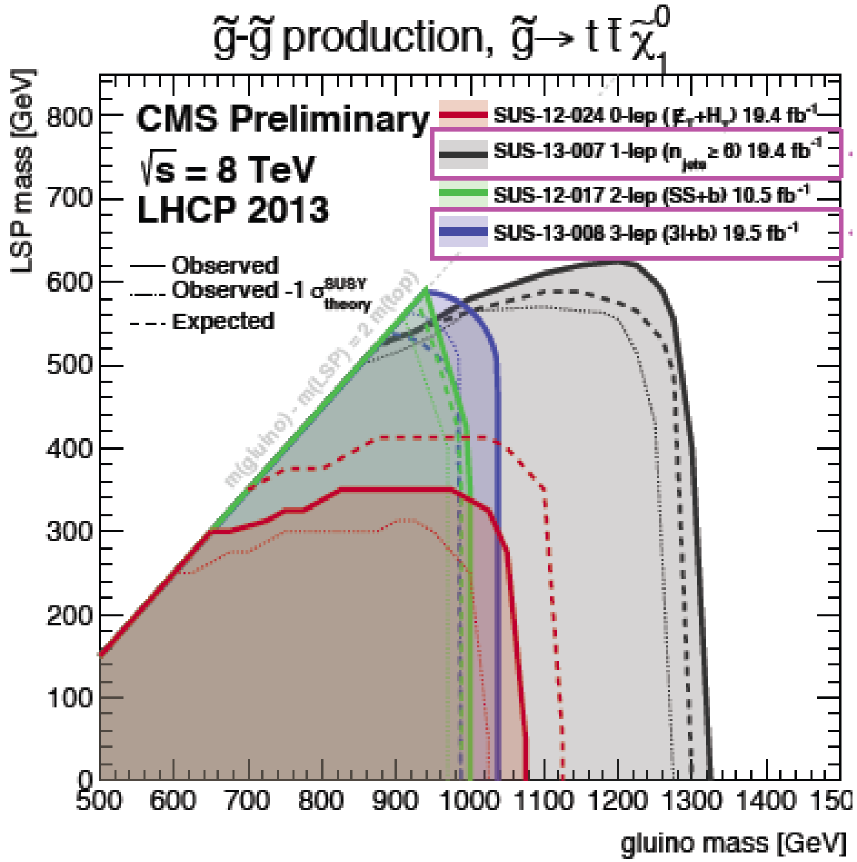
s-top

Searches for stops, gluinos, sbottoms target natural SUSY

- Probe stops up to ~650 GeV
- Probe gluinos up to ~1.3 TeV
- Probe sbottoms up to ~600 GeV

CMS





Is naturalness relevant? The multiverse alternative

- 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

Actually applying the anthropic principle to the SM hierarchy problem is not terribly convincing

After all, we can find plenty of models that reduce the fine tuning from 10^{14} to 10^{2}. And the added ingredients would not make our existence more impossible.
So why make our Universe so terribly unlikely?

One can argue that the case of the cosmological constant is a lot different: the context is not as fully specified as the for the SM

A revival of models that ignore the fine tuning problem

Examples:

Split SUSY
heavy scalars, light gauginos and higgsinos (DM and Unification)

High scale SUSY
all sparticles heavy
λh^4 fixed by gauge

Non SUSY GUT's
Unificaxion
Giudice, Rattazzi, Strumia
Non SUSY SO(10)
GA, Meloni
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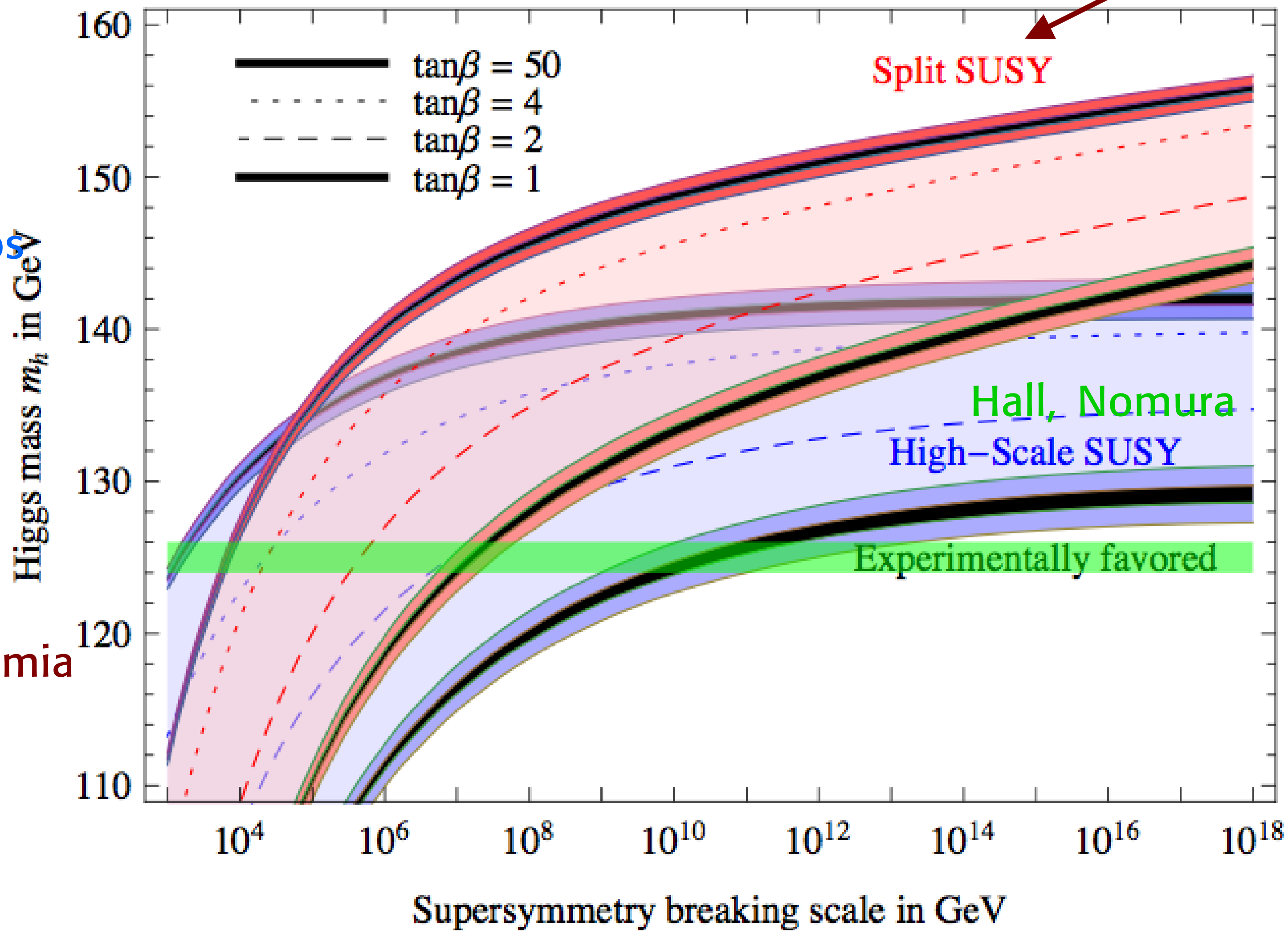
Giudice, Strumia

Arkani-Amed,Dimopoulos
Giudice, Romanino



The absence of new physics appears as a paradox to us

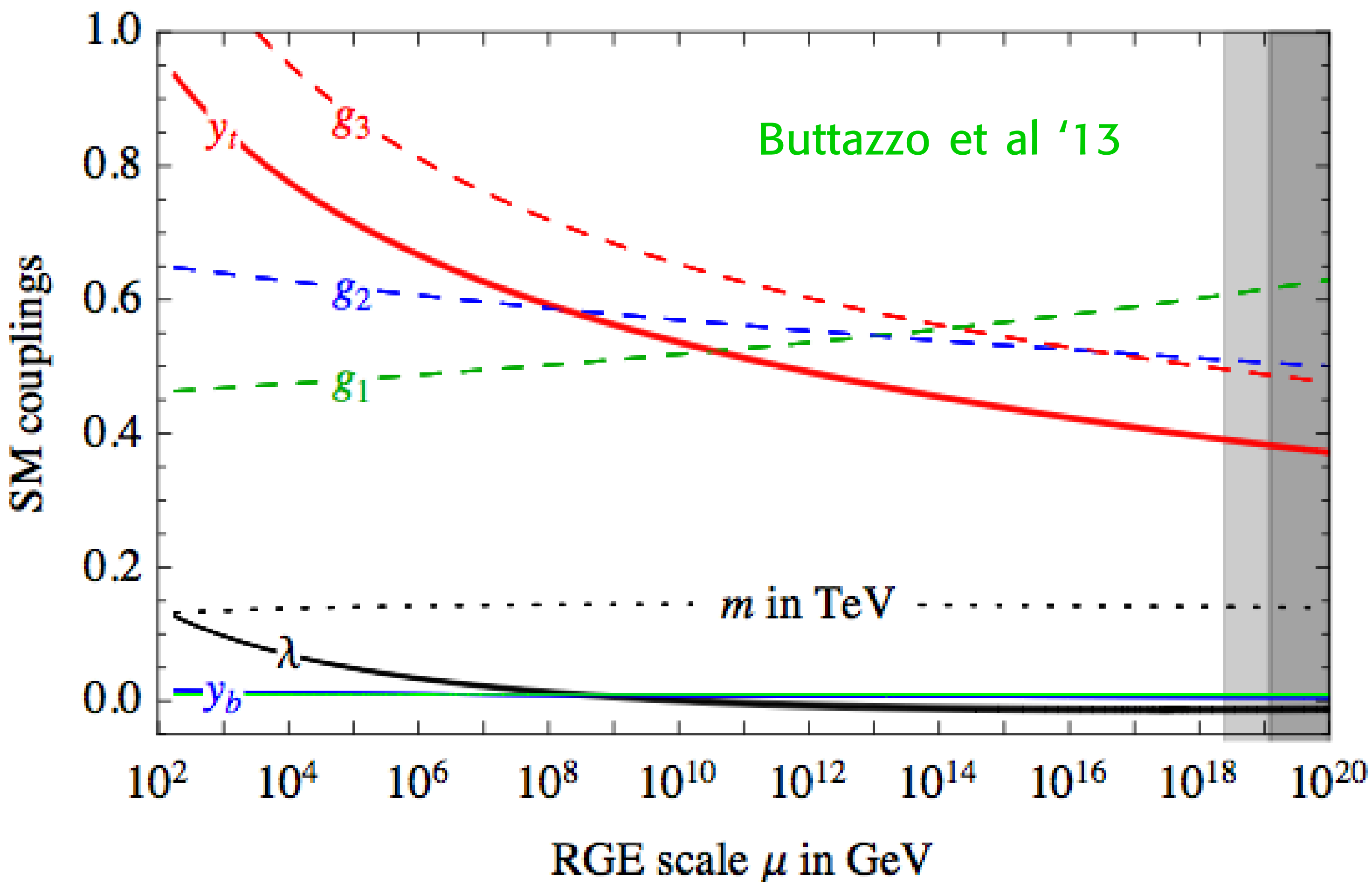
Still the picture suggested by the last 20 years of data is simple and clear:

Take the SM, extended to include Majorana neutrinos, as the theory valid up to very high energy

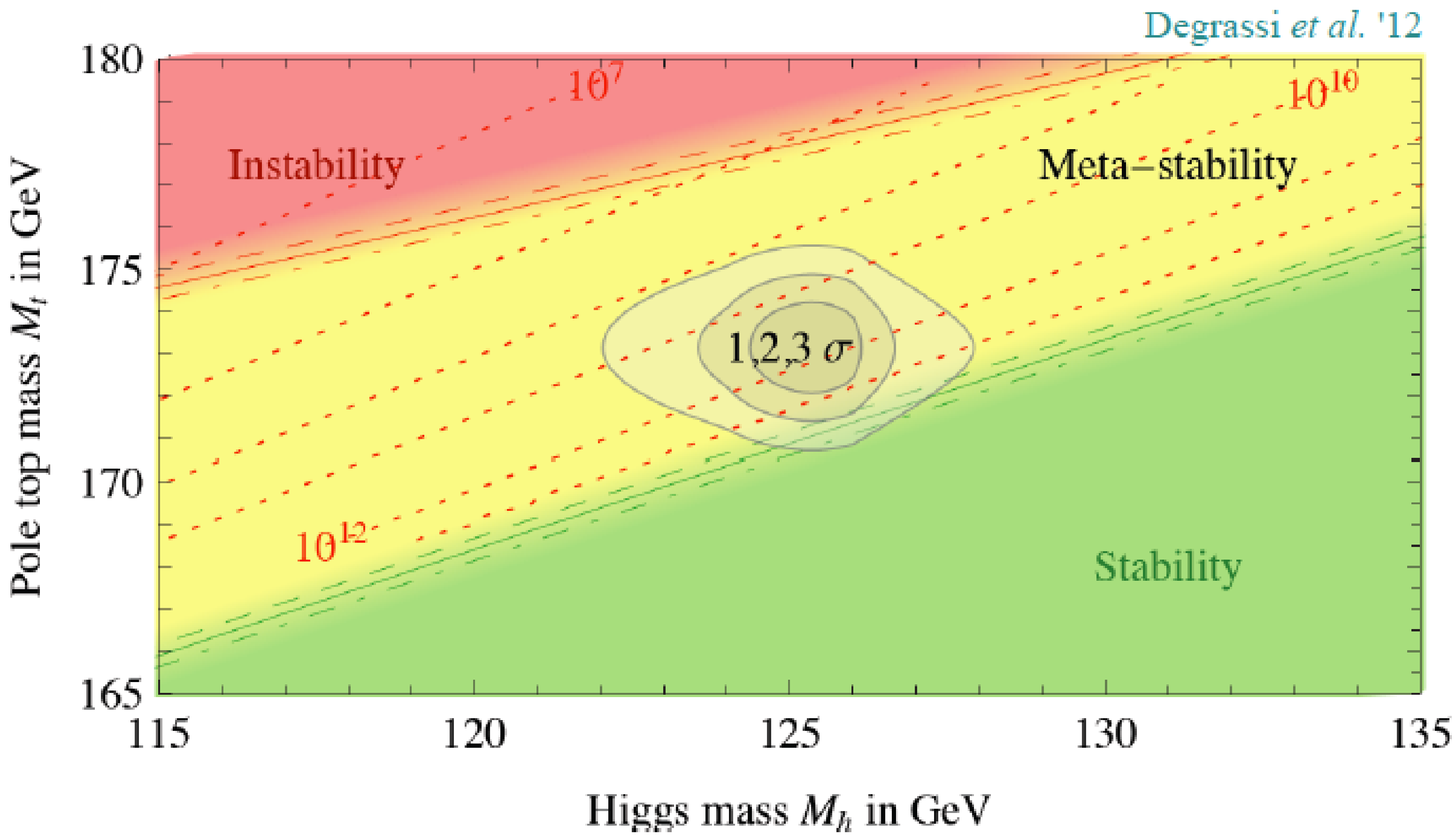
Dark Matter? Axions
Baryogenesis? Thru leptogenesis
Coupling Unification? SO(10) with an intermediate scale

Possibly Nature has a way, hidden to us, to realize a deeper form of naturalness at a more fundamental level

State of the art coupling evolution in SM (3 loops, thresholds)



In the SM for m_H ~ 126 GeV the SM vacuum is metastable



Buttazzo et al '13

Close to the critical line

Absolute stability condition

$$M_h\ [\mathrm{GeV}] > 129.4 + 2.0\left(\frac{M_t\ [\mathrm{GeV}] - 173.1}{1.0}\right) - 0.5\left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right) \pm 1.0_{\rm th}$$

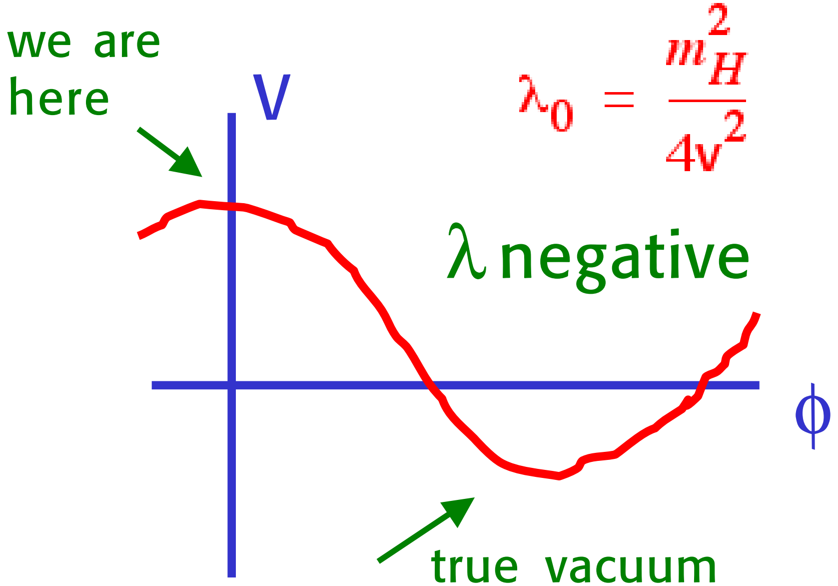
For the measured values both λ and $\beta(\lambda)$ vanish near M_{Pl}

see e.g. Shaposhnikov; Wetterich '10

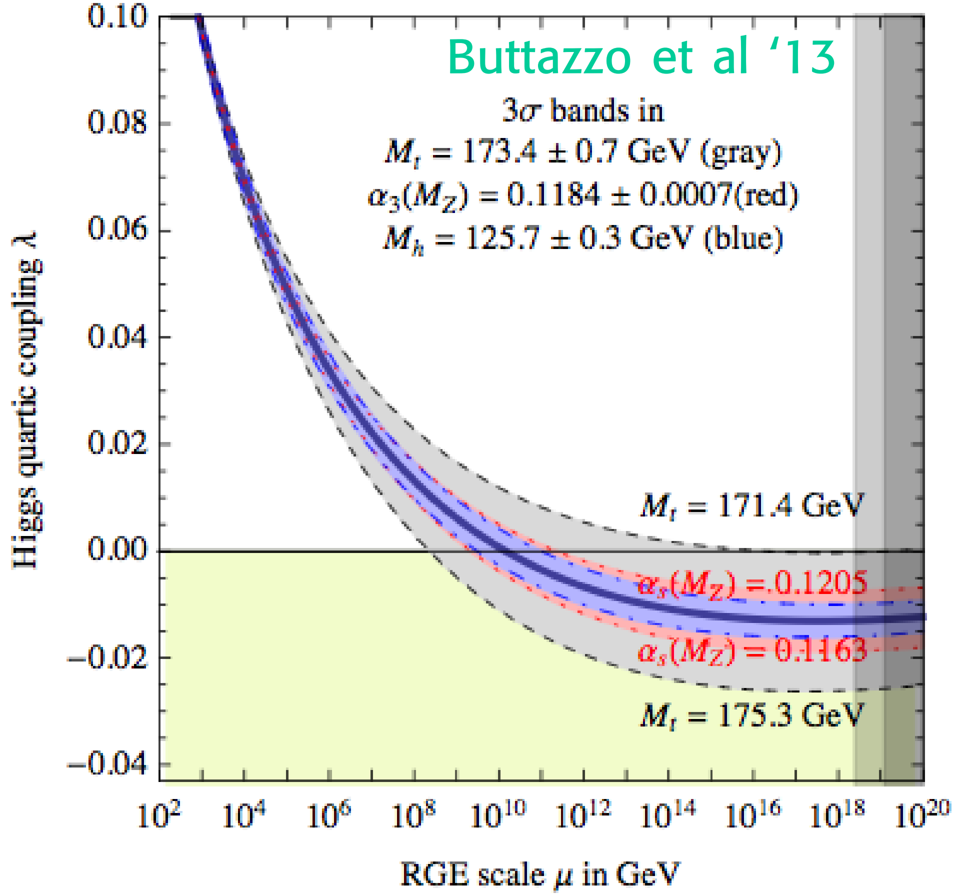
But metastability (with sufficiently long lifetime) is enough!

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

$$\lambda_0 = \frac{m_H^2}{4v^2}$$



(something is assumed to stabilize V at ~ M_{Pl})



In the absence of new physics, for m_H ~ 126 GeV,
the Universe becomes metastable at a scale $\Lambda \sim 10^{10\text{-}12}$ GeV

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

Dark Matter is the most compelling argument for New Physics

WIMP's still are optimal candidates:
Weakly Interacting Massive Particle with m ~ 10^1-10^3 GeV

LHC can reach any kind of WIMP

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

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

can work for typical weak cross-sections!!!

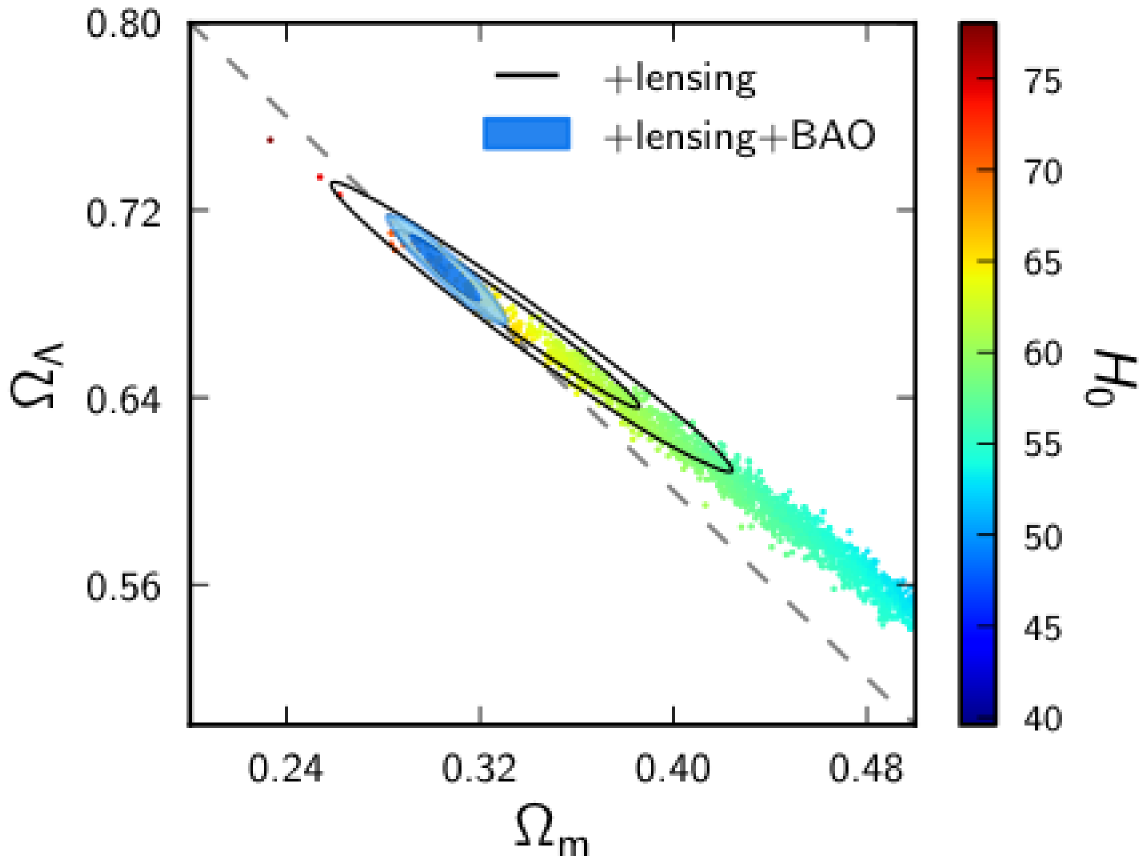
This "coincidence" is a good indication in favour of a WIMP explanation of Dark Matter

A "simple" cosmology emerges from Planck

More precise values of cosmological parameters

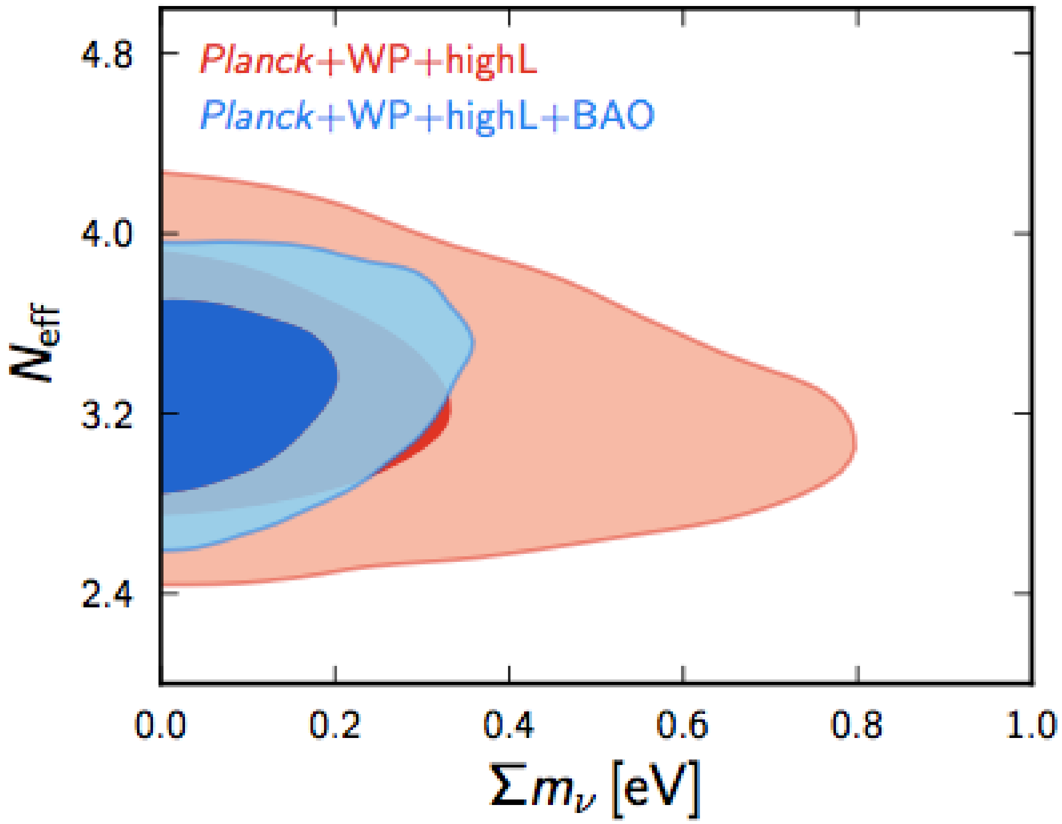
Ω_Λ=0.686±0.020
Ω_m=0.314±0.020
$\Omega_b h^2$=0.02207±0.00033
h=0.674±0.014

ΛCDM confirmed



No evidence for sterile neutrinos

$N_{eff}=3.36\pm0.34$



$\Sigma m_\nu < 0.23$ eV

DM searches and the Higgs boson

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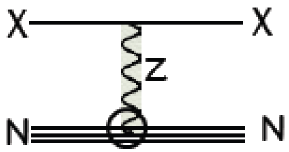
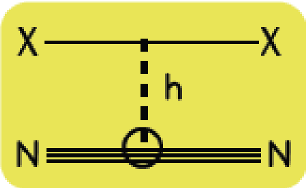
$\chi N \to \chi N$

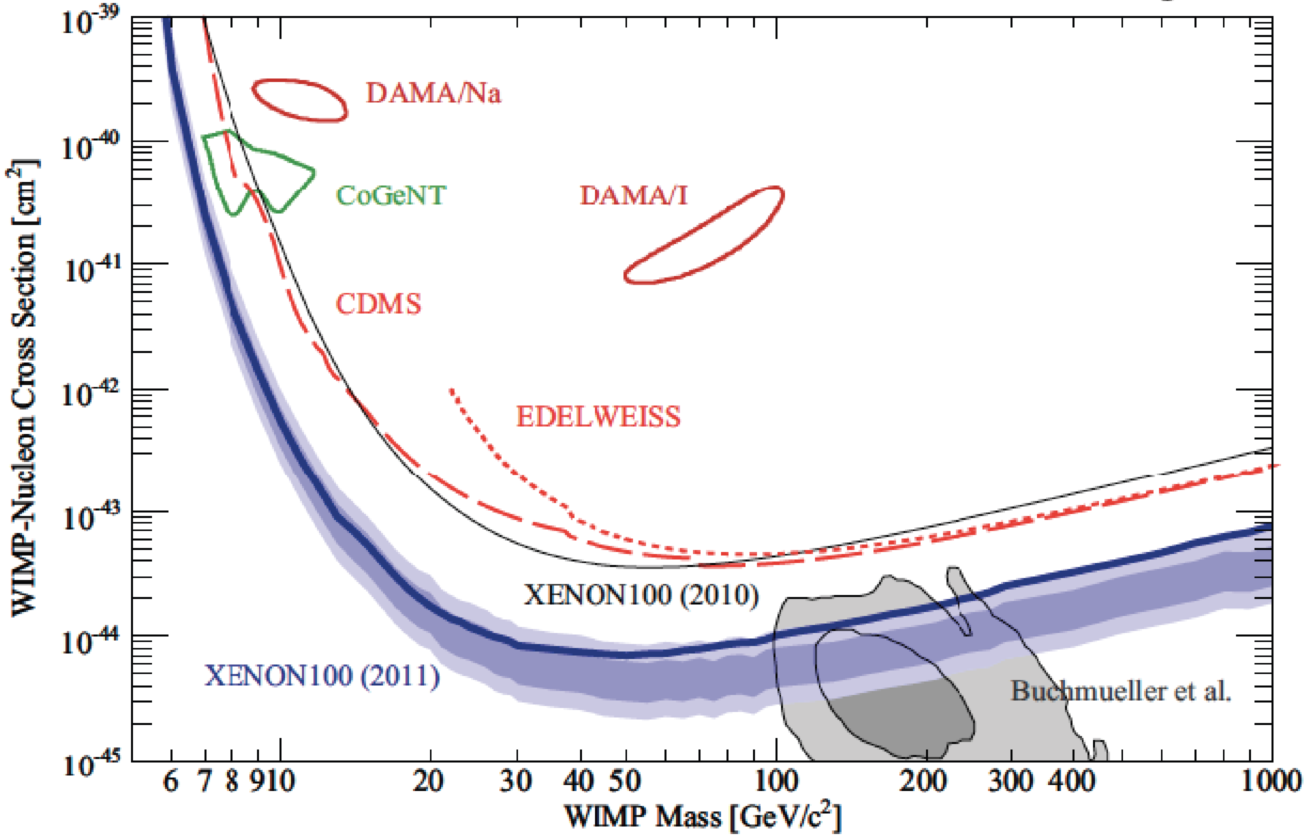
3 events/1.8 backgd

$\sigma_Z(\chi N)$ spin indep. excluded since long time





exclusion by XENON100 (100 days x 48 kgs)

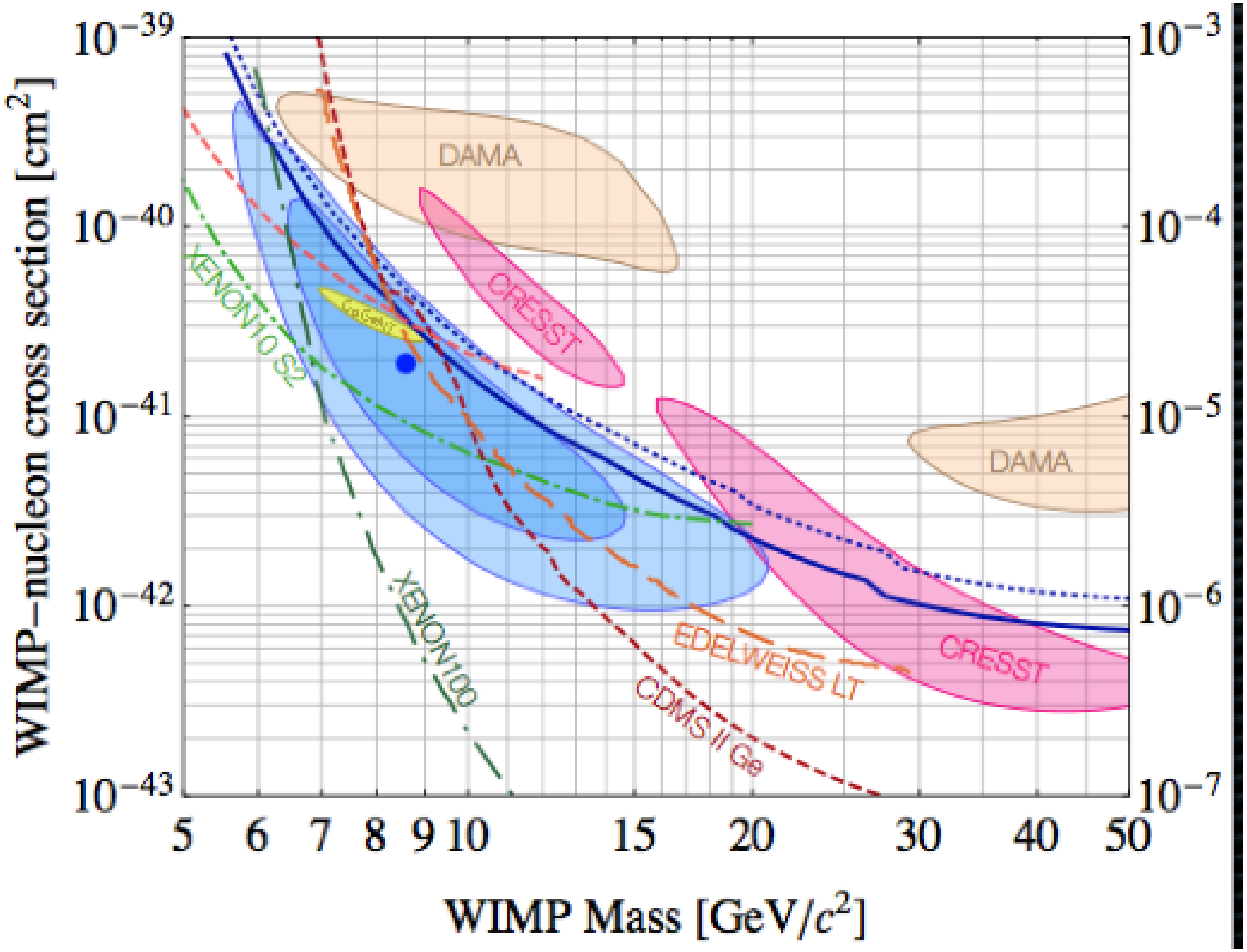


Higgs boson exchange being probed now for $m_h = 125\ GeV$

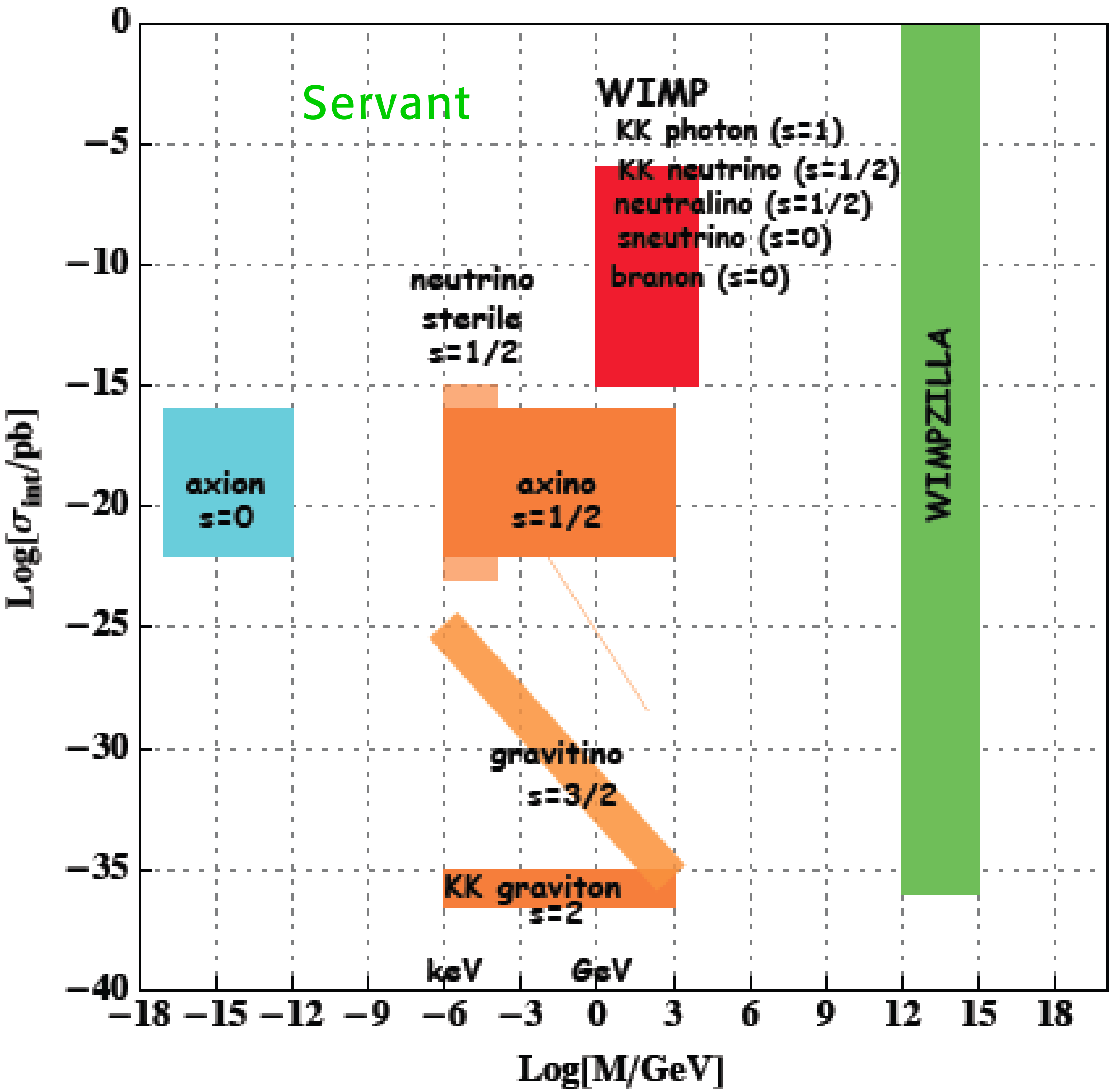
$$\sigma_h(\chi N) \approx 10^{-43} cm^2\ (\frac{\lambda}{0.1})^2 (\frac{100 GeV}{m_\chi})^2 (\frac{100 GeV}{m_h})^4$$

CDMS-Si ArXiv :1304.4279

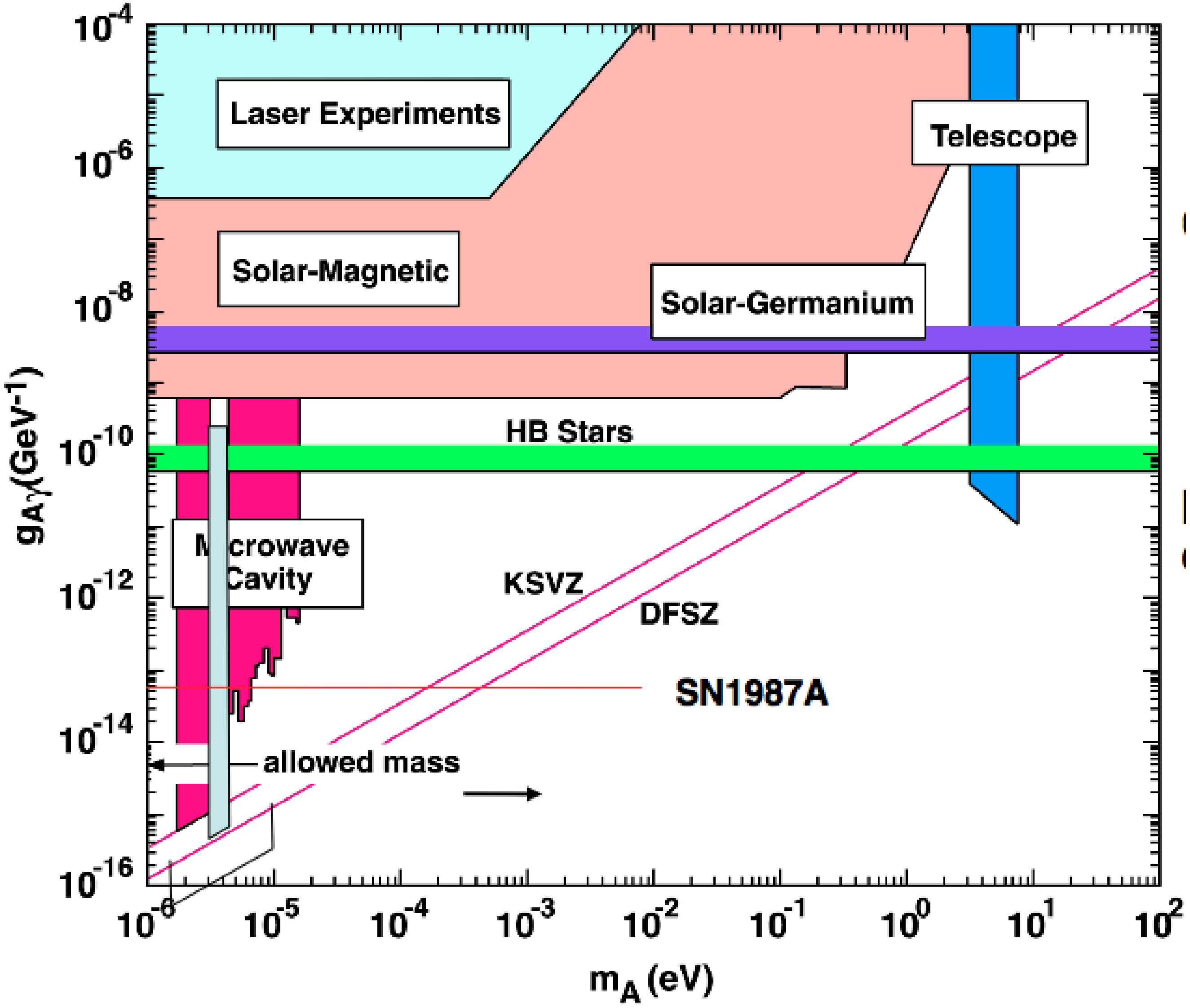
Low mass
~10 GeV
WIMPS?



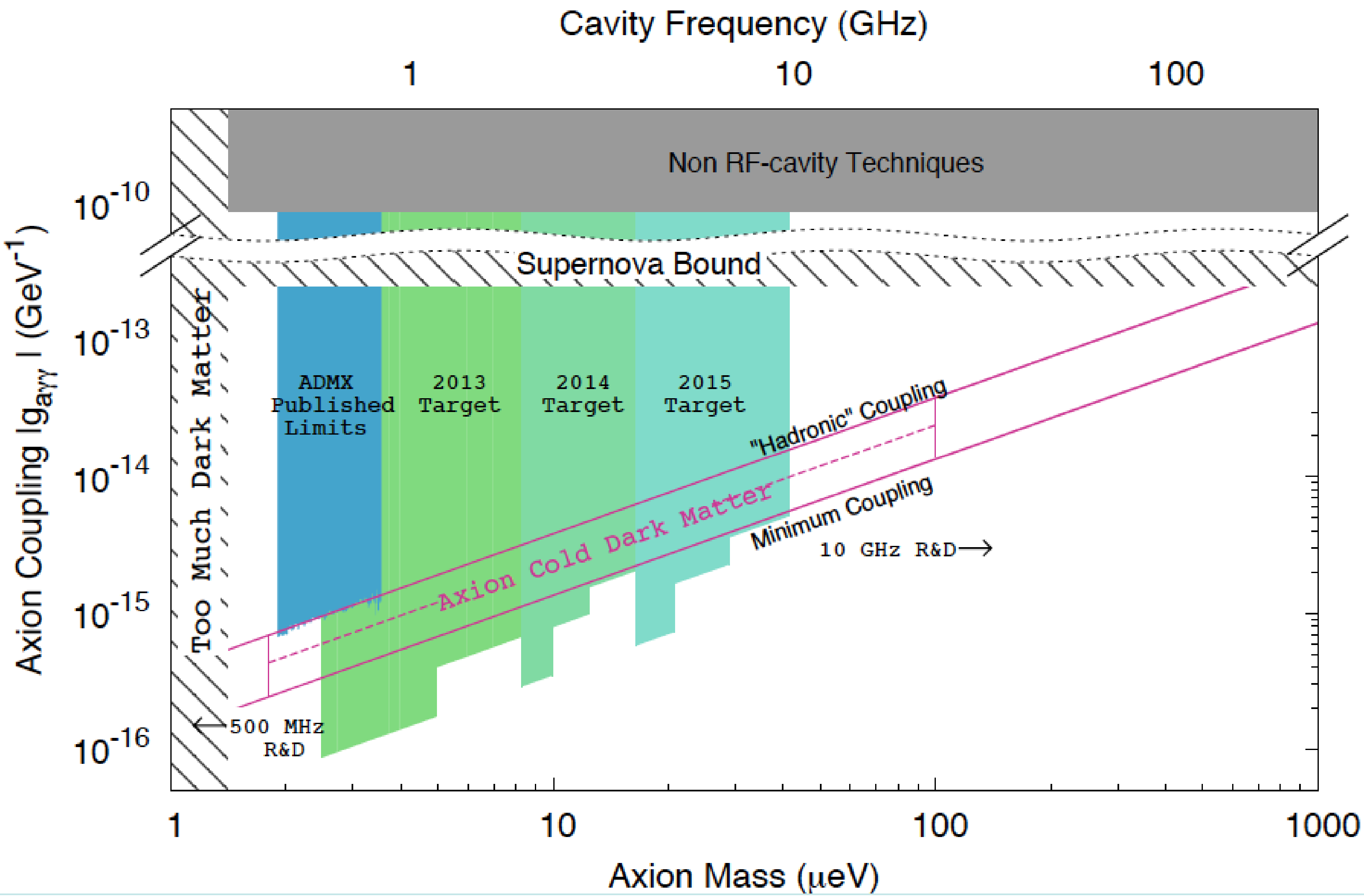
Of all DM candidates the axion is the closest to the SM



Axion searches are very important



ADMX: an experiment for axion search



An explicit model: GA, Meloni ArXiv:1305.1001

An enlarged SM (to include RH ν's, coupling unification in GUT) valid up to a large scale is an (enormously fine tuned) option

following the anthropic philosophy, the Multiverse, the Landscape

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 ($\sim 10^{11}$ GeV)
[coupling unification, p-decay OK]

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

Baryogenesis thru leptogenesis

Axions as dark matter (axion searches)

recall that $\mu \to e \gamma$, edm of neutron.... are not seen!

No new physics at the LHC
[$(g-2)_\mu$ and other present deviations from SM in colliders should be disposed of]

Conclusion from the LHC at 7 - 8 TeV

A particle that looks very much like the simplest elementary SM Higgs has been found

The exp. verification of the SM is complete

The first example of a fundamental, weakly coupled, scalar particle with VEV

No evidence of new physics. We expected complexity and we found simplicity

So far naturalness was not a good heuristic guiding principle. But the final outcome is still open

A change of perspective is taking place: many unnatural models are being studied. Even the Multiverse and the anthropic philosophy are gaining credit

Precise tests of the Higgs couplings and further searches for new physics will be done in the next few years at 8 - 14 TeV

CERN future ---> Schumacher   ILC --> Yamamoto   Future machines --> Murayama

Conclusion (no lack of ? marks)

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1. Natural or unnatural theories?

before accepting a shift of paradigm,
useful to be patient and careful (but courageous as well)

2. One or more Higgs bosons?

could be the lightest new particle(s) around
need a better exp $\Leftrightarrow$ theory communication

3. What about the flavour puzzle?

$m's, V_{CKM} \Leftrightarrow \lambda_{ij}^{Yukawa}$: a great embarrassment,
unlikely to be solved without much needed key data

4. The Multiverse?

Yes, perhaps, but then what?

SUMMARY (AFTER 125 HIGGS)

Pokorski

NO REASON YET TO:

- GIVE UP THE QUESTION ABOUT THE ORIGIN OF THE FERMI SCALE AS A GUIDING PRINCIPLE FOR THE BSM PHYSICS*
- TO RUSH TO THE LANDSCAPE PICTURE FOR THE FERMI SCALE

THE EXPERIMENTAL EXPLORATION OF THE TeV SCALE IS STILL IN A VERY PRELIMINARY STAGE

MEANWHILE:
INCREASE PRECISION OF THE SM PREDICTIONS AND EXP RESULTS FOR THE h
FILL IN EXPERIMENTAL LOOPHOLES LIKE E.G. A LIGHT SCALAR SEARCH IN PHOTON-PHOTON CHANNEL

*) **SHOULD WE BECOME MORE OPEN MINDED, E.G. WITH RESPECT TO THE QUANTIFICATION OF THE CONCEPT OF NATURALNESS OR IN SEARCHING FOR NON-MINIMAL MODELS;**

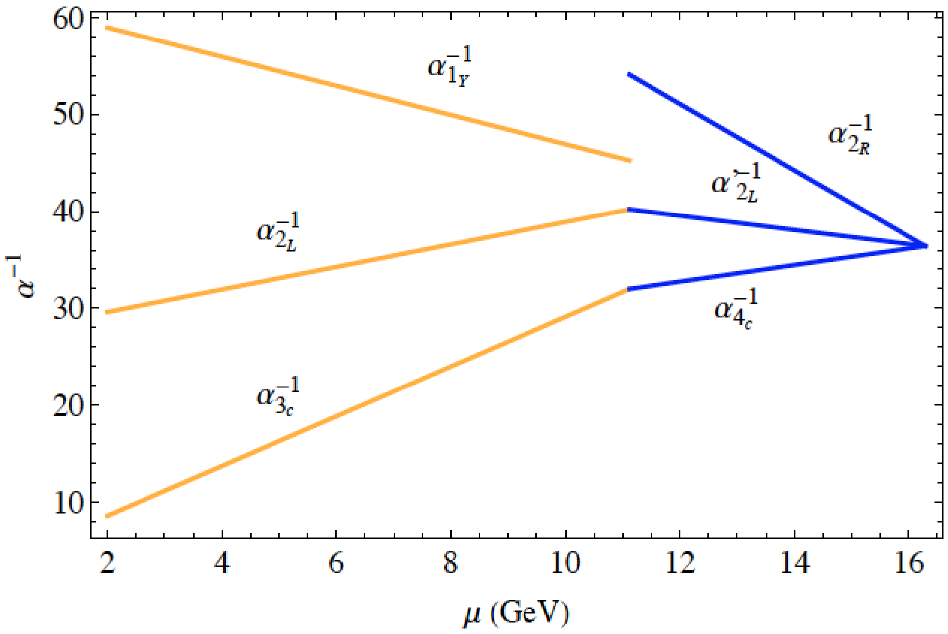
We worked out an explicit model: GA, Meloni ArXiv:1305.1001

$$SO(10) \xrightarrow{M_{GUT}-210_H} 4_C\, 2_L\, 2_R \xrightarrow{M_I-126_H,45_H} 3_C\, 2_L\, 1_Y \xrightarrow{M_Z-10_H} 3_C\, 1_Y$$

The imposed constraints are sufficiently restrictive that only a particular breaking chain with PS symmetry at M_I works

	210_H	$\overline{126}_H$	45_H	10_H
M_{GUT}	all components	$(6,1,1),(\overline{10},3,1)$	$(1,3,1),(6,2,2),(15,1,1)$	$(6,1,1)$
M_I	$-$	$(10,1,3),(15,2,2)$	$(1,1,3)$	$-$
EW	$-$	$-$	$-$	$(1,2,2)$

$$M_I = (1.3 \pm 0.2)\cdot 10^{11}\,\mathrm{GeV} \qquad M_{GUT} = (1.9 \pm 0.6)\cdot 10^{16}\,\mathrm{GeV}$$



obs.	*fit*	*pull*	*obs.*	*fit*	*pull*
m_u(MeV)	0.49	0.03	$\|V_{us}\|$	0.225	0.038
m_d(MeV)	0.78	0.75	$\|V_{cb}\|$	0.042	−0.208
m_s(MeV)	32.5	−1.50	$\|V_{ub}\|$	0.0038	−0.659
m_c(GeV)	0.287	−1.49	J	3.1×10^{-5}	0.589
m_b(GeV)	1.11	−2.77	$\sin^2\theta^l_{12}$	0.318	0.611
m_t(GeV)	71.4	0.70	$\sin^2\theta^l_{23}$	0.353	−1.548
r	0.031	0.10	$\sin^2\theta^l_{13}$	0.0222	−0.758
η_B	5.699×10^{-10}	−0.001			

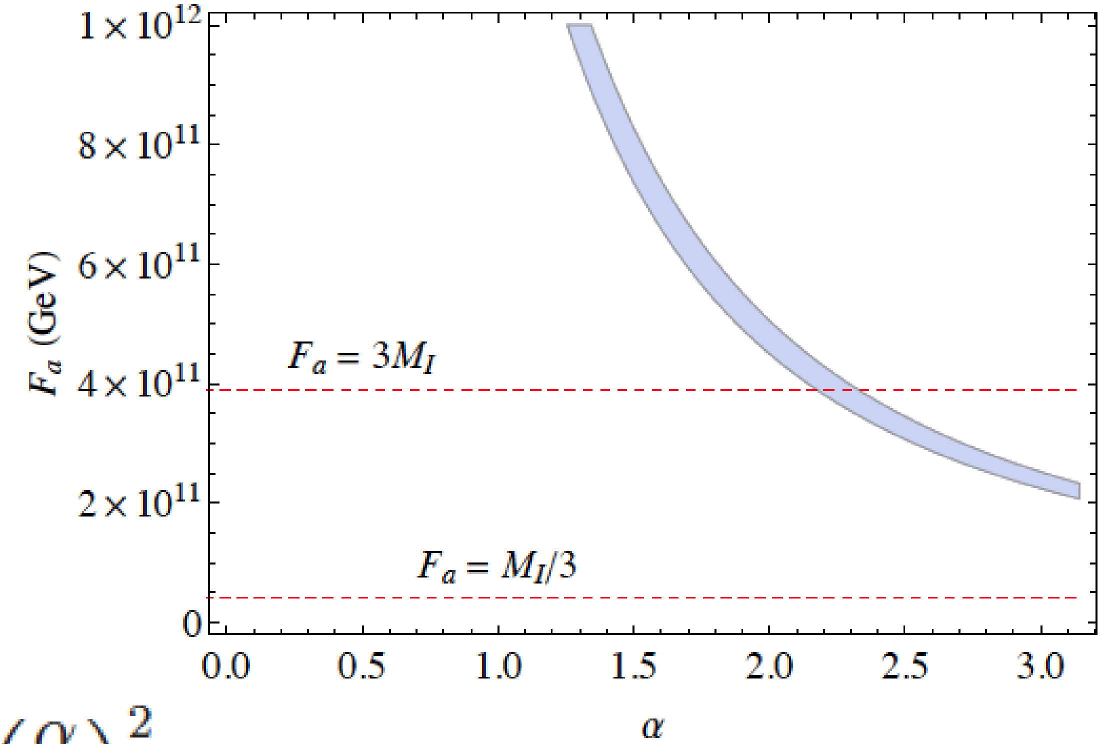
leptogenesis → η_B

Best fit solutions for the fermion observables at the scale $M_{GUT} = 2 \cdot 10^{16}$ GeV.

Predictions

p-decay
$\tau > 10^{36}$ yrs

$light\ \nu\ masses\ (eV)$	$heavy\ \nu\ masses\ (10^{11}\ GeV)$	$phases\ (^\circ)$	$m_{ee}\ (eV)$
.0046	1.00	$\delta = 88.6$	5×10^{-4}
.0098	1.09	$\phi_1 = -33.2$	
.0504	21.4	$\phi_2 = 15.7$	



Axions can reproduce the correct amount of DM

$$m_a = \frac{z^{\frac{1}{2}}}{1+z}\,\frac{f_\pi m_\pi}{F_a}$$

$$\Omega_a h^2 \approx 0.7 \left(\frac{F_a}{10^{12}\,\mathrm{GeV}}\right)^{\frac{7}{6}} \left(\frac{\alpha}{\pi}\right)^2$$