Learning from the LHC

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String Phenomenology
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The message from the LHC *so far*
(see previous talk by Alcaraz)

The minimal, weakly-coupled SM
with a single “elementary” scalar doublet

works far beyond most expectations

against tests at growing precision and energy

There was evidence before from
LEP, Tevatron, B-factories, etc

Stronger and more direct evidence
after the first run of the LHC

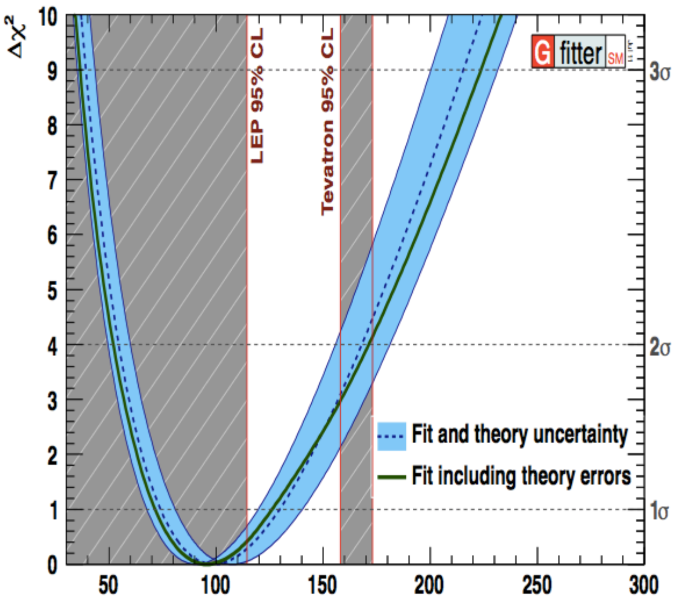
($\sqrt{S}$ =7-8 TeV, ~25 fb^{-1})

The H boson is there @ $m_H \approx 125$ GeV it looks *so far* SM-like

- Mass where favoured by EW precision tests
- Couplings to vectors and fermions as in SM
- No signs of exotic states in γγ or gg loops
- No signs of mixing with other states
- No signs of invisible decay channels
- No signs of additional Higgs bosons

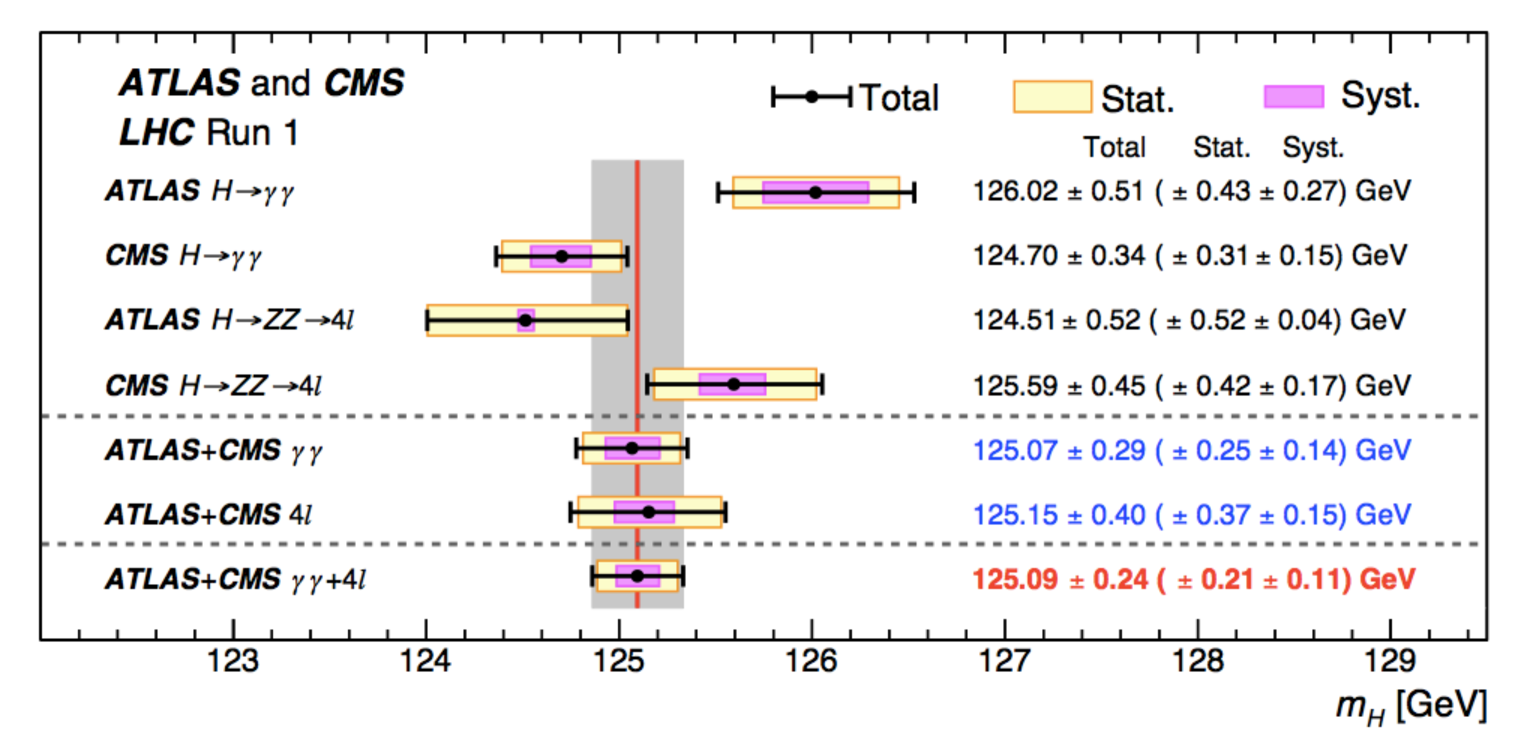
...all with still large errors, but...

SM fit to EWPT in 2011 →



Combined Higgs mass from ATLAS and CMS Run 1 data (at 2 per mille accuracy!)

↓

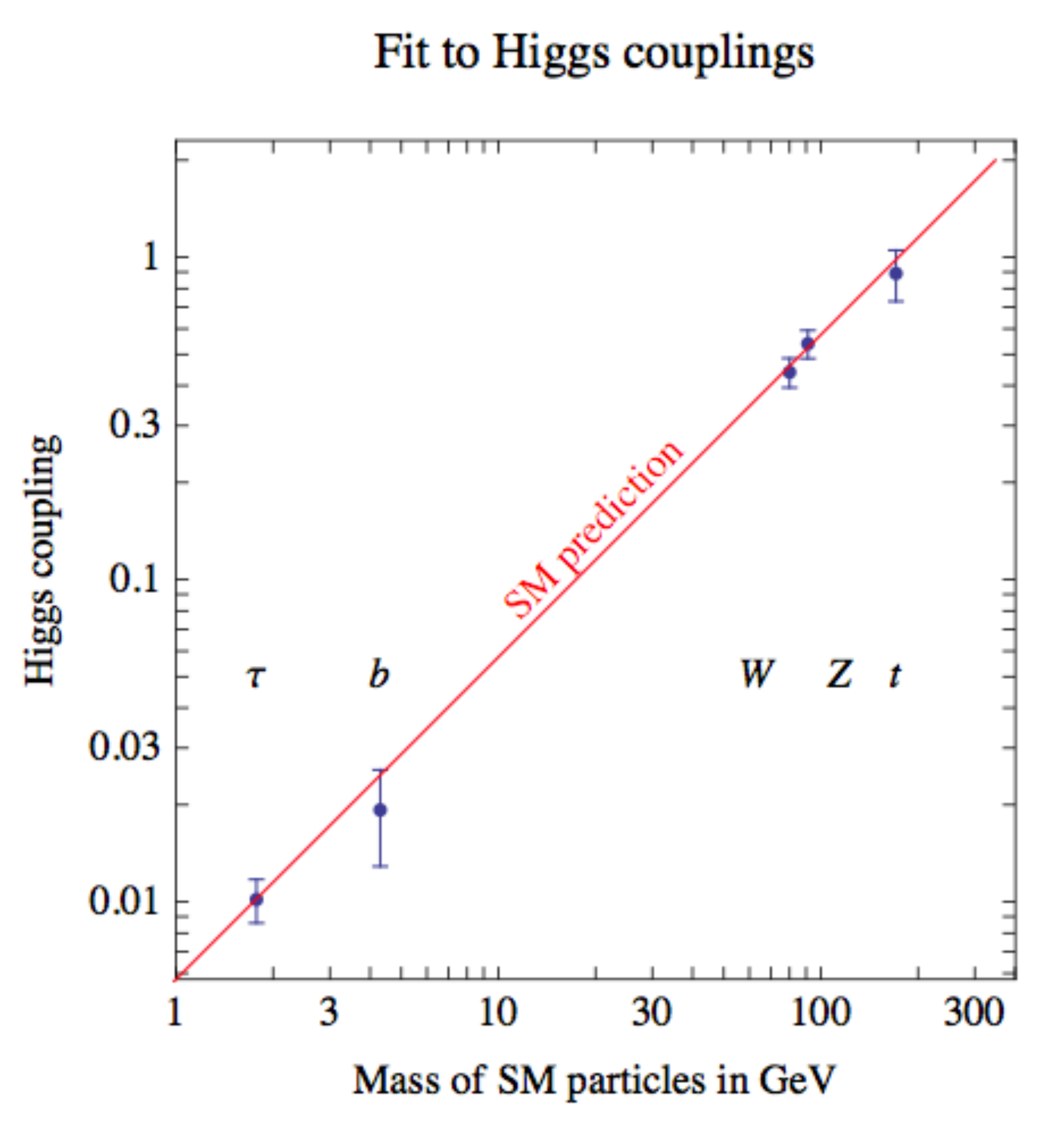


Giardino, Kannike, Masina, Raidal, Strumia

"The universal Higgs fit"

Based on ATLAS & CMS data as of Summer 2014

Waiting for the official LHC combination



… SM precision tests cannot be ignored … 59 d=6 operators, 17 involving H, 8 affecting only H physics, all the others already constrained by EWPT

8 primary Higgs couplings

for one family *(assuming CP-conservation)*

$$\Delta\mathcal{L}_{\rm BSM} = \delta g_{hff}\, h\bar{f}_L f_R + h.c. \quad (f=b,\tau,t)$$
$$+ g_{hVV}\, h\left[W^{+\,\mu}W^-_\mu + \frac{1}{2\cos^2\theta_W}Z^\mu Z_\mu\right]$$
$$+ \kappa_{GG}\frac{h}{v}G^{\mu\nu}G_{\mu\nu}$$
$$+ \kappa_{\gamma\gamma}\frac{h}{v}F^{\gamma\,\mu\nu}F^\gamma_{\mu\nu}$$
$$+ \kappa_{\gamma Z}\frac{h}{v}F^{\gamma\,\mu\nu}F^Z_{\mu\nu}$$
$$+ \delta g_{3h}\, h^3$$

6 measured at the LHC

H→Zγ can still be 9 x SM

gg→hh a challenge for HL-LHC

Pomarol@Naturalness 2014

Elias-Miro, Espinosa, Masso, AP, JHEP 1311 (2013) 066
AP, Riva, JHEP 1401 (2014) 151

Further precision tests in flavour physics

An example: $B_s \rightarrow \mu^+ \mu^-$

$BR_{LHCb+CMS}=(2.9\pm0.7)\times10^{-9}$ $BR_{SM}=(3.56\pm0.30)\times10^{-9}$

Could have received sizeable contributions from New Physics

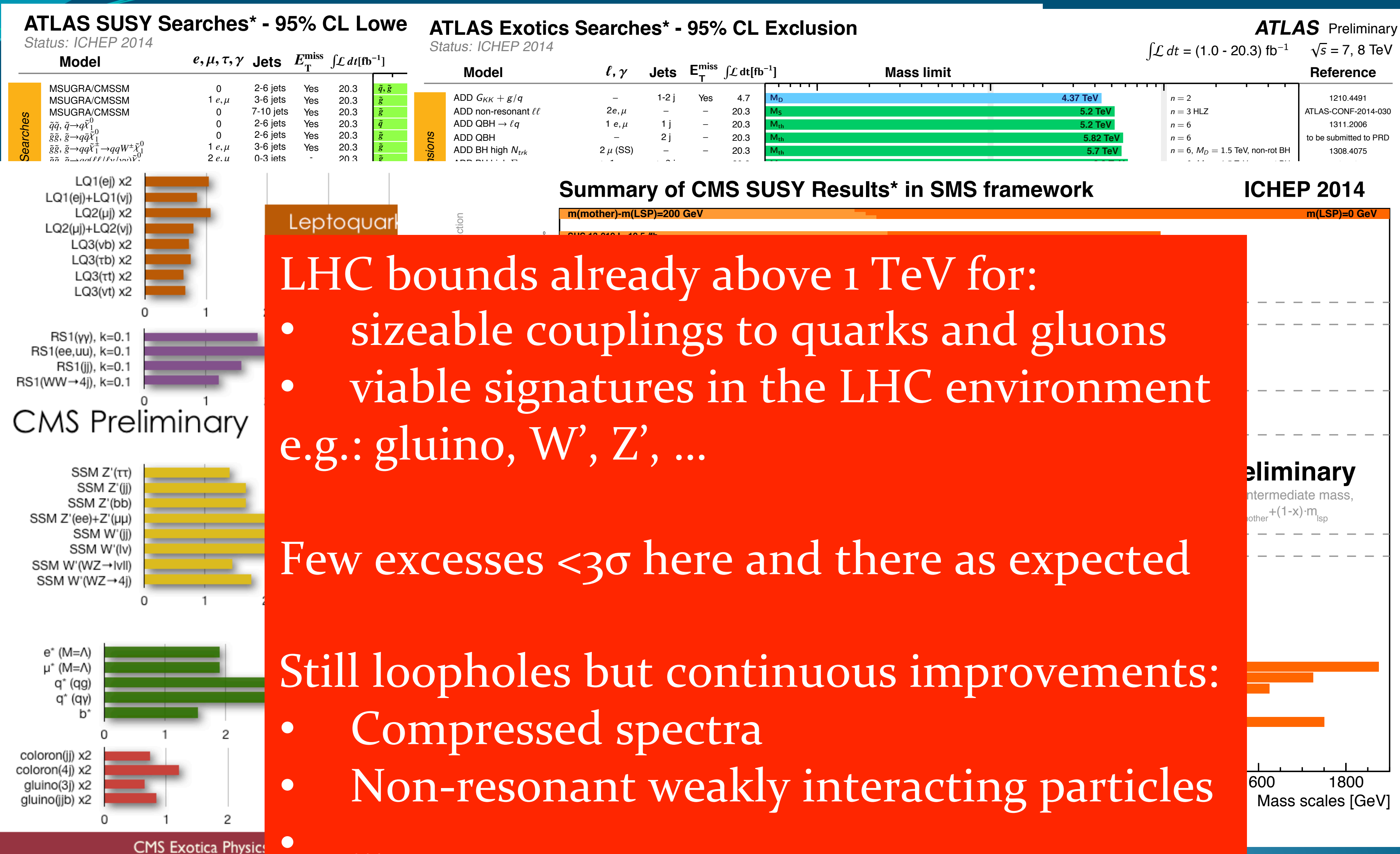
FCNC & CP-violating processes involving quarks consistent with CKM matrix as only source of flavour violation (generalized GIM cancellations at work)

Stringent bounds also on FCNC with charged leptons

e.g. 2013 MEG bound $BR(\mu\rightarrow e\gamma) < 5.7 \times 10^{-13}$ (90%cl)

Negligible in SM, comparable in many New Physics models

No new particles found *so far*



LHC bounds already above 1 TeV for:

- sizeable couplings to quarks and gluons
- viable signatures in the LHC environment

e.g.: gluino, W’, Z’, …

Few excesses <3σ here and there as expected

Still loopholes but continuous improvements:

- Compressed spectra
- Non-resonant weakly interacting particles
- …

Naturalness revisited: SM as EFT

Λ = effective UV cutoff (not necessarily universal)
= the scale of some (unspecified) new physics

$$L_{eff}^{SM} = \Lambda^4 + \Lambda^2\Phi^2 \qquad (\Lambda^{n>0} \Rightarrow \textit{ hierarchy problems!})$$

$$+ (D\Phi)^2 + \overline{\Psi}\, \not{D}\Psi + F\cdot F + F\cdot\widetilde{F} + \overline{\Psi}\Psi\Phi + \Phi^4$$

$$(\textit{controllable } \log\Lambda \textit{ dependence via quantum corrections})$$

$$+ \frac{\overline{\Psi}\Psi\Phi^2}{\Lambda} + \frac{\overline{\Psi}\sigma^{\mu\nu}\Psi F_{\mu\nu}}{\Lambda} + \frac{\overline{\Psi}\Psi\overline{\Psi}\Psi}{\Lambda^2} + \frac{\Phi^2 F^{\mu\nu}F_{\mu\nu}}{\Lambda^2} + \ldots$$

$$(\Lambda^{n<0} \Rightarrow EW\ tests,\ \ flavour\ tests,\ \ \not{B},\ \ \not{L},\ \ \ldots)$$

Naturalness (Dirac, Weisskopf, Wilson, Weinberg, 't Hooft)

coefficients small only because of symmetries

Works at face value in many cases:

- Electron mass in NR QED ➔ positron

$$\delta m_e \sim \alpha \Lambda \quad \to \quad \delta m_e \sim \alpha m_e \log \ldots$$

- 4-f FCNC box diagram with 3 light q ➔c

$$G_F^2 \Lambda^2 \sim G_F^2 m_W^2 \ \textit{too large!} \quad \to \quad G_F^2 m_c^2 \ OK$$

- π^+ - π^0 mass difference in QED ➔ ρ

$$\Delta m_\pi^2 = (3\alpha)/(4\pi)\Lambda^2 \ \to \ \Lambda \sim m_\rho \ OK$$

but not for the cosmological constant …

Weak scale naturalness challenged

No quantum SM symmetry recovered for $m_H \rightarrow 0$
Unprotected ratio m_H/M for any scale $M >> m_H$
[Subtleties if scale invariance explicitly broken only by quantum corrections and not by UV physics? How?]

$$\delta m_H^2 \sim -\frac{3\,h_t^2}{8\,\pi^2}\,\Lambda^2 < O(m_H^2) \quad \rightarrow$$

$\Lambda < O(500)$ GeV

SM unnatural unless New Physics at the TeV

A challenge already after LEP, Tevatron, B-factories
Now much more severe after Run 1 of the LHC

The nightmare of many theorists

stimulus for many recent theoretical attempts

Almost natural SUSY?

Some bottom-up options with softly broken SUSY:

- Mechanism (e.g. singlet) to raise the Higgs mass
- Lower mediation/cutoff scale (no large logs)
- Split spectrum: keep light only those states more directly coupled to H (stop, gluino, higgsino)
- R-parity violation (with baryon-number): lose main collider signature (missing p_T) thus weaker bounds
- Dirac gauginos (motivated by N=2 supersymmetry) no log Λ for scalar masses, less squark production

Pragmatical inspiration to broaden the LHC searches

Rather ad hoc, each with some drawbacks at present

Almost natural compositeness?

Traditional technicolor models technically natural, but ruled out by EW precision tests and in trouble with heavy fermion masses already before the LHC
Overkilled by discovery of light SM-like Higgs

Still viable compositeness [review by Panico-Wulzer 2015]:

- H is composite state of a new strong force
- H light because pseudo-Goldstone boson
- SM fermions (e.g. top) coupled linearly to the new strongly interacting sector

Naturalness controlled by $\xi = v/f$ ($\Lambda_s \leq 4\pi f$)
Light Higgs correlates with light top partners

Neutral naturalness?

Both classes of models discussed above predict
light colored top partners to be probed by LHC-13

LHC Run 2 as final test of naturalness?
a lot of recent interest in neutral naturalness

Example: Twin Higgs [Chacko, Goh, Harnik 2005]
Mirror copy of the SM coupled via Higgs portal
SO(8)/SO(7) GB: 3(W/Z) + 3$(W/Z)_M$ + 1(H)
Neutral naturalness for softly broken Z_2
Recent embeddings in field-theory orbifolds,
SUSY, compositeness [Craig et al 2015, Barbieri et al 2015]

Different attempt in the next talk by Kaplan

Back to supersymmetry. Why?

- Departing from MSSM may improve naturalness
- Can still accommodate gauge unification and DM for heavier spectra beyond the present LHC reach (lose on naturalness, improve on h~SM & flavour)
- Might need to combine SUSY and some additional ingredient to solve the SM naturalness problem, more insights may still come from supergravities
- The role of supersymmetry in QFT and string theory beyond (today's) particle phenomenology

Now three hierarchy problems

HUGE

$$\langle V \rangle^{1/4}/M_P \sim 10^{-30}$$ vacuum energy

LARGE

$$G_F^{-1/2}/M_P \sim 10^{-16}$$ gauge hierarchy

LITTLE

$$\frac{m^2_{W,Z,h}}{m^2_{sparticles,extra\,H}} \lesssim 10^{-2}$$

LHC-8: SM-like scalar h at 125 GeV,
new bounds on H,A,$H^{\pm}$ & s-particles

Seemingly unnatural SUSY

(see e.g. Arvanitaki et al arXiv:1210.0555 and refs. therein)

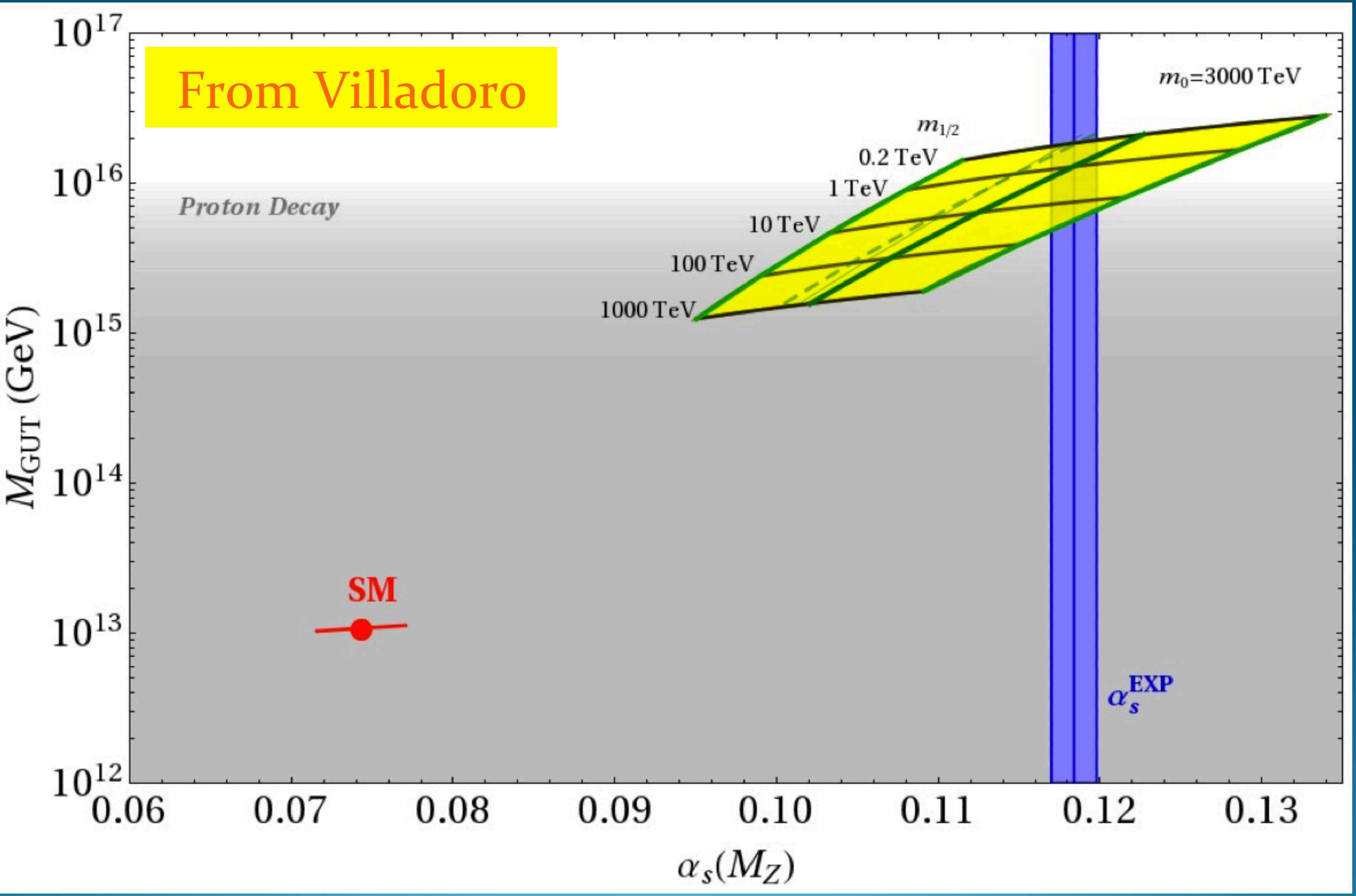
If we ignore SUSY problems with fine-tuning

SUSY, TeV-scale gauginos, heavier scalars
(hierarchy protected by R-symmetry)

evade present LHC direct bounds
evade present flavour constraints
can reproduce SM-like H at 125 GeV
compatible with gauge unification
compatible with (TeV-scale) LSP as DM

Will the LHC energy be enough?

Good old gauge coupling unification



Naturalness in supergravity

Confronting SUSY with naturalness, are we missing subtle possibilities with gravity?

Supergravity most suitable framework to study some problems, e.g. vacuum selection once we identify the correct symmetries

A possibility worth further exploration: non-compact global symmetries in no-scale models

N=1 no-scale models

(Cremmer-Ferrara-Kounnas-Nanopoulos 1983; ...)

- $V_o \geq 0$ in a finite moduli space with broken SUSY ➔ classical flat background without fine-tuning
- Susy-breaking scale classical flat direction: might generate $v \sim m_{susy} << M_P$ by perturbative quantum corrections a la Coleman-Weinberg, if no quadratic UV sensitivity is present
- Even assuming that quadratic sensitivity is cured by the UV completion, little hierarchy problem: should get $v << m_{susy}$ to evade the LHC8 bounds

A small recent step forward

[Dall'Agata, FZ 2013; Luo, FZ 2014]

N=1 no-scale model (F- and D-breaking) with SUSY & SU(2)xU(1) broken on Minkowski

only 2 real flat directions:

x<->$m_{3/2}$ <-> massless "dilaton" t

v <-> $m_{W,Z}$ <-> massless SM Higgs h

[pseudo-Goldstones in SO(2,5)/SO(2)xSO(5)]

Higgsino & (H,A,$H^{\pm}$) with masses ~ $m_{3/2}$

(before quantum corrections)

May this help with the little hierarchy?

Need more work on couplings to matter

Back to experimental prospects:

From the 80s on, all collider discoveries
(W/Z, t, H) strongly "guided" by theory

No-lose theorems applicable in each case,
based on general theoretical arguments
such as unitarity and/or anomaly freedom,
helped focusing the experimental strategies

We won't be again in such a condition for some time
Role of experiment not less important than before
diversify now efforts to maximize chances
(until either a new experimental discovery
or a new compelling theory emerge)

Collider physics for the years to come

1. Find out whether H is accompanied by other new particles near the TeV scale

2. Study H properties with the highest possible precision, seeking inconsistencies of the SM that would point indirectly to new physics

3. Push further precision tests of flavour physics

LHC *so far*:

4/7 of design c.o.m energy, < 1/10 (1/100) of design (achievable with HL-LHC) integrated luminosity

Not only collider physics

First evidence of new physics scales not bound to come from high-energy colliders (their negative results equally important for our understanding)

Some other potential breakthroughs:

total lepton number violation from $(\beta\beta)_{0\nu}$ decay

the scale of inflation from polarisation in the CMB

direct detection of dark matter (axion? WIMP? …)

An outlook, rather than conclusions

In the coming decades we will concretely address, on multiple fronts, several fundamental questions

Naturalness, Dark Matter, Scale of Inflation, …

The current LHC run is a major opportunity, progress guaranteed whatever the findings

Timing and options for the final answers
more open then in the last 30 years
but this is what makes this field exciting

Thank you for your attention