Higgs Couplings 2013
Concluding Remarks

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Karl, Markus and Stefan

- *Not a summary*
- *A conclusion held with confidence but not substantiated by proof*

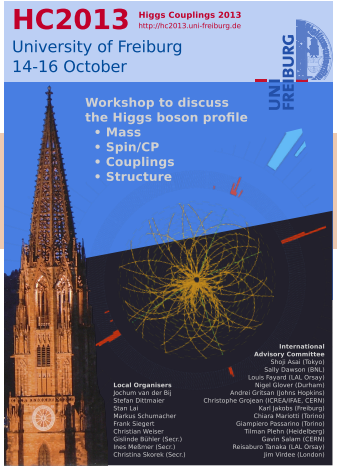
  The world is not run by thought, nor by imagination, but by opinion (Elizabeth Drew).
- *A collection of visions, scenarios and approaches*

Iliopoulos, Velasco, Malone, Forte, Mueck, Tarrade, De Florian, Gritsan, Henandez Jimenez

Mawatari, Qjan, Petrucciani, Rauch, Gonzalez-Garcia, Zanetti, Tanabe, Botta, Reece, Ceballos

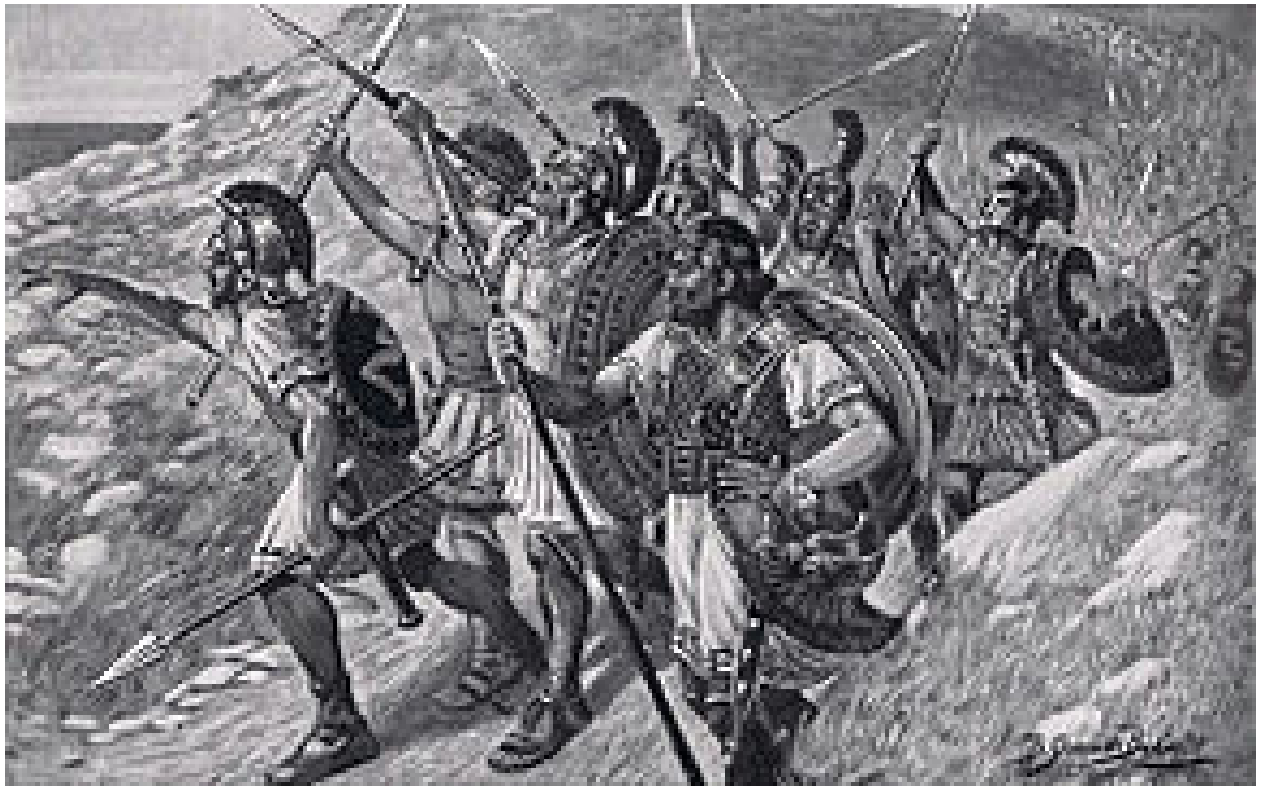
Redi, Rotondo, Gori, Bressler, Englert, Degrassi

talkS



THE LHC BOSON: the Xenophon - vision

Θάλαττα Θάλαττα (Anabasis: Book 4, Chapter 7, Section 24).



THE LHC BOSON: the Hieronymus Bosch - vision (you are there)

MSM *triumph of thinking simple*

- ⇛ LHC(**125**) looks very much like the (light) SM Higgs boson The exp. discovery is fundamental but *wasn't already clear* 20 *years ago?*
- **NO LHC signal of New Physics**. But ... (*debatable*) aren't precision Lep data, precision flavour data, etc. pointing in that direction? e.g. consistency with **EW precision data** ↛ no conspiracy between heavy Higgs and NP effects

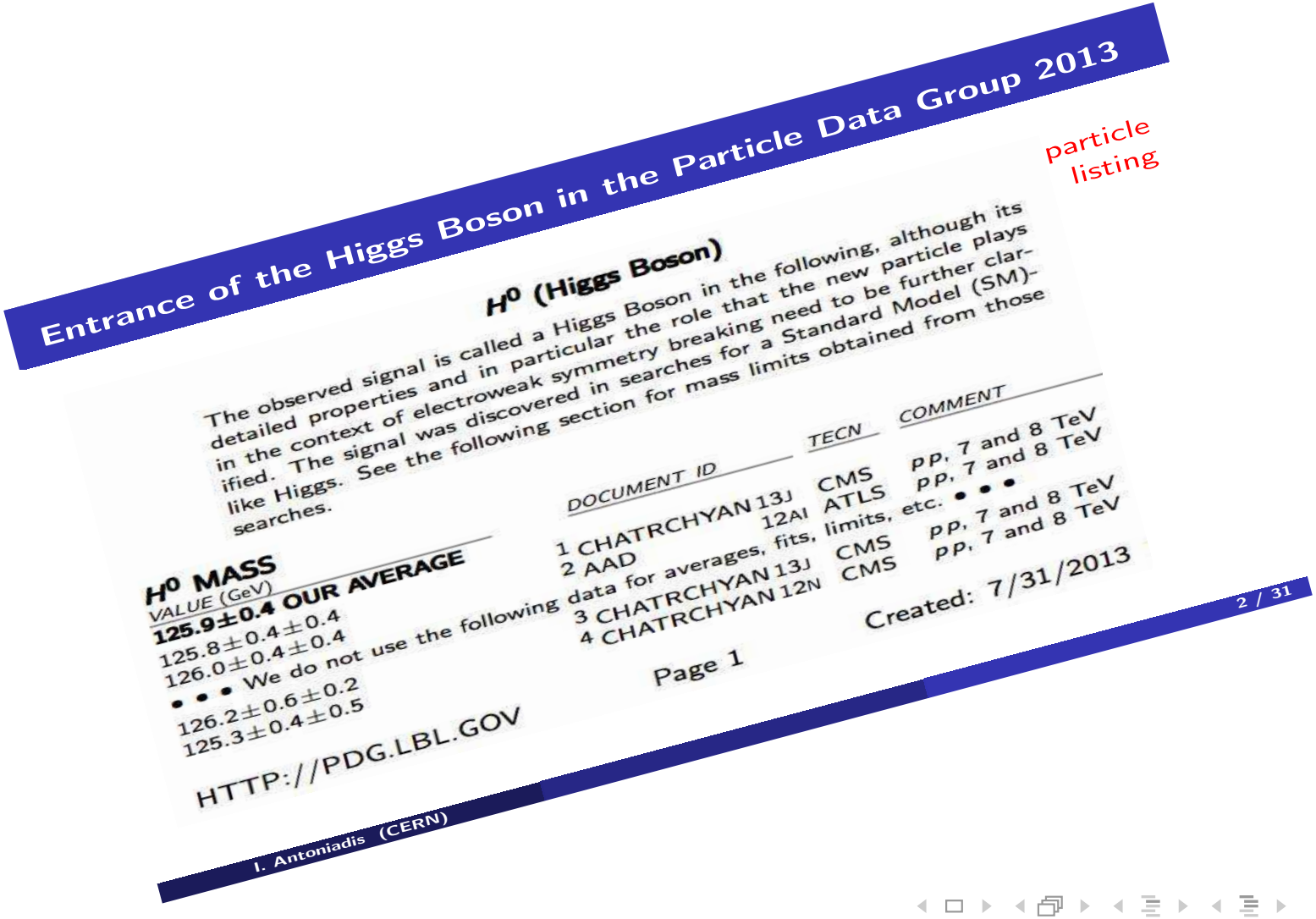
There is nothing either good or bad but thinking makes it so

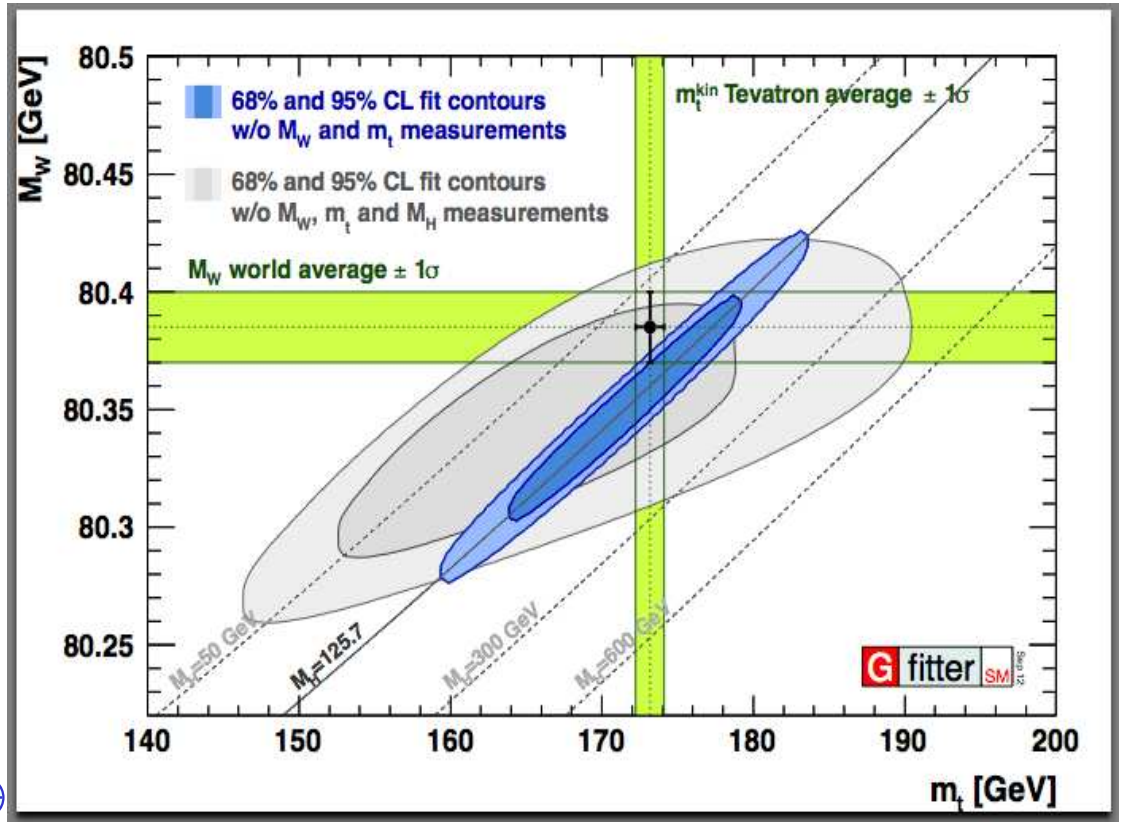
(William Shakespeare)

Were you expecting NP around the corner?

If you align expectations with reality, you will never be disappointed

I'm thrilled that this year's Nobel Prize has gone to particle physics **Rolf Heuer**




80.5
80.45
80.4
80.35
80.3
80.25
M_W [GeV]
140
150
160
170
180
190
200
m_t [GeV]
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

Intermezzo As Summary Speaker I am somewhat ambivalent subdued about the affair.

- **THE SM** *has now got a degree of validity that has extended way beyond what we had before the discovery of a Higgs-like particle*
- *However,* *the one aspect that dominates here* *is that a Higgs could close the last door of the SM that could lead us to a deeper theory*

To love SM is to not always agree with SM . It is usually right, but not always right

Is SM(**125**) the FINAL THEORY ? Maybe no

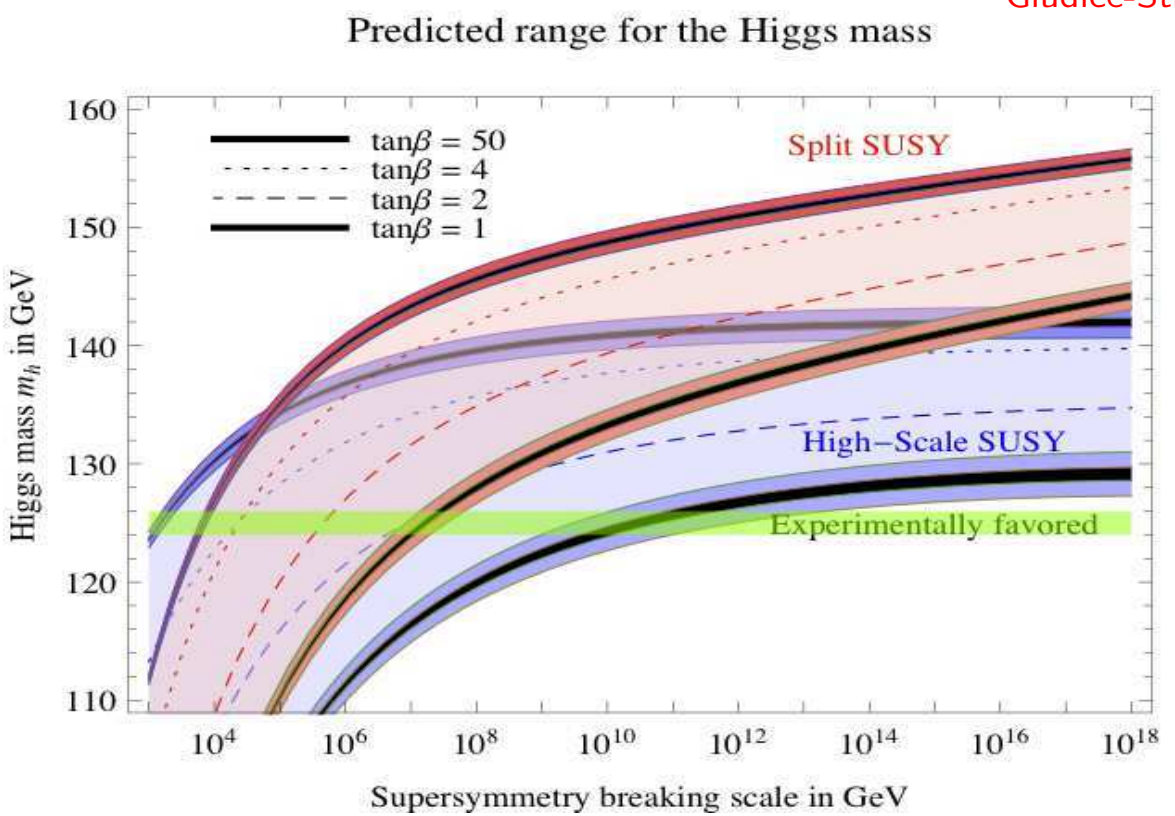
Problems

- hierarchy problem
- dark matter
- ν-mass, BAU
- inflation
- cosmological constant
- gauge coupling unification
- strong CP

Additionally, there is *no scientific reason to justify the belief that all the big problems have solutions*, let alone ones we humans can find.

Scales & Susy

Giudice-Strumia '11



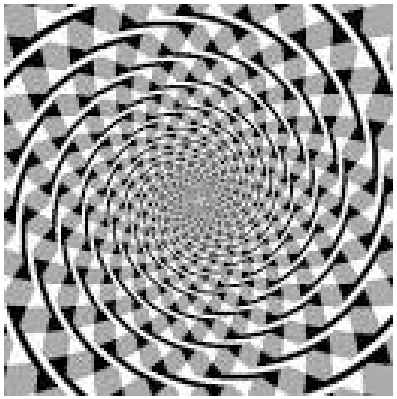
What about Hierarchy? nature choosing fine-tuning? *nothing new*

- CNO - cycle (stars convert hydrogen to helium)
- if gravity stronger or weaker by **1** part in $\mathbf{10^{40}}$, then life-sustaining stars like the sun could not exist

If we nudge one of the constants just a few percent in one direction, stars burn out within a million years of their formation, and there is no time for evolution. If we nudge it a few percent in the other direction, then no elements heavier than helium form. No carbon, no life. Not even any chemistry. No complexity at all (D. D. Deutsch)

- size of sun-moon from earth . . . , many more in the $\mathbf{10^{3-4}}$ ballpark (neutron/proton mass ratio, initial explosion of big bang, etc.)

It is worth remembering how well *classical Ptolemaic epicycles* could predict astronomical positions *despite being based on false (but highly-tuned) Roman science*



The pessimistic LHC scenario (PS) :

would be nothing but the SM at LHC energies and no detection of dark matter (the recent discovery could complete the Standard Model but the result from the Planck satellite shows that normal matter is only five percent of the energy density of the Universe)

The PTOLEMAIC approach : *forget some of the problems (hierarchy, gauge coupling unification, strong CP). Extend SM*

- Introduce real scalar DM ✓

$$\mathscr{L}_S = -m_S^2 S^2 - g_S \|\Phi^2\| S^2 - \lambda_S^2 S^4$$

- Introduce two ν_R and leptogenesis ✓

$$\mathscr{L}_{\nu R} = -M \overline{N}^c N + y_\nu L \tilde{} \overline{N}$$

- Introduce real scalar inflaton ✓

$$\mathscr{L} = -m^2 \phi^2 - \mu \phi^3 - \kappa \phi^4$$

- Forget about cosmological constant, call it **MBSM** (Minimal Beyond Standard Model)

Do we need more than **MBSM** (also known as Altarelli cocktail* **2**)?

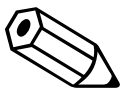
The regulative ideal of an ultimate theory remains a powerful *aesthetic ingredient* (**perhaps too kantian?**)

★ **2/3** of SM, **1/6** of Majorana neutrinos, **1/6** of axions, add Peccei - Quinn global symmetry, strain the result

The optimistic scenario (OS) :

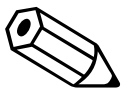
is the usual picture sold pre-LHC: detection of non-SM Higgs.

Some of us are optimist, but gave no argument for the optimistic scenario beyond the one that it's a good idea in life for a scientist to be an optimist



A concrete (forget gravity) **OS** wish list:

- Systematizing THU in the sense of MHO and MHOU : accuracy over precision. THU in differential form (jets, p_T, η, etc.)
- Beyond **NWA**
- Decays: weird (vector meson) and rare (Dalitz)
- Anything that would use the Higgs as a probe for **BSM**



- Marrying EW precision data with Higgs
- General **EWSB** aspects (dibosons, $\mathbf{VV}$-scattering) and **EW** fits (M_t, M_W, α_s, etc.)
- Predictions/generators to constrain the (finally agreed upon) **EFT** coupling space, esp. using Higgs plus other data (like EW data as mentioned above).

PRECISION?

next step

ILC plans to provide the next significant step in the precision study of Higgs boson properties. LHC precision measurements in the **5–10%** range sould be brought down to the level of **1%**.

But this means that the κ*-language must be updated with the inclusion of* **NLO EW**. *This means*

- ✂ No precision for precision's sake!
- ✌ Precision for a discovery search

The UTTERLY SIMPLE vision

To my mind, there must be at the bottom of it all, not an utterly simple equation, but an utterly simple IDEA. And to me that idea, when we finally discover it, will be so compelling, and so inevitable, so beautiful, we will all say to each other, "How could it have ever been otherwise?"

(John Wheeler)

ILC plans to measure σ_{ZH}. Once again, this is a pseudo-observable

Precision Physics : *restricting our attention to the relative merits of realism and instrumentalism.*

Do we have a way of knowing whether "unobservable" theoretical entities really exist, or that their meaning is defined solely through measurable quantities?

What does the term "Higgs decay" or σ_{ZH} *mean? A mathematical expression? But what does it mean for such an expression to exist in the physical world? Trying to answer that question immediately raises other questions about the correspondence between mathematical objects and the physical world*

Signal strengths

LHC projections

Different scenarios assumed by the two experiments

- ATLAS: with and without th error (same exp. syst. as
- CMS: Scenario 1 and Scena

EWK production modes (st theory error) allow over large theory uncertainty fusion production

Aim at 5% for the main fiv analyses

5%

ATLAS

$\Delta\mu/\mu$	300 fb^{-1}		3000 fb^{-1}	
	All unc.	No theory unc.	All unc.	No theory unc.
$H \to \mu\mu$ (comb.)	0.39	0.38	0.15	0.12
(incl.)	0.47	0.45	0.19	0.15
(ttH-like)	0.73	0.72	0.26	0.23
$H \to \tau\tau$ (VBF-like)	0.22	0.16	0.19	0.12
$H \to ZZ$ (comb.)	0.12	0.06	0.10	0.04
(VH-like)	0.32	0.31	0.13	0.12
(ttH-like)	0.46	0.44	0.20	0.16
(VBF-like)	0.34	0.31	0.21	0.16
(ggF-like)	0.13	0.06	0.12	0.04
$H \to WW$ (comb.)	0.13	0.08	0.09	0.05
(VBF-like)	0.21	0.20	0.12	0.09
(+1j)	0.36	0.17	0.33	0.10
(+0j)	0.20	0.08	0.19	0.05
$H \to Z\gamma$ (incl.)	1.47	1.45	0.57	0.54
$H \to \gamma\gamma$ (comb.)	0.14	0.09	0.10	0.04
(VH-like)	0.77	0.77	0.26	0.25
(ttH-like)	0.55	0.54	0.21	0.17
(VBF-like)	0.47	0.43	0.21	0.15
(+1j)	0.37	0.14	0.37	0.05
(+0j)	0.22	0.12	0.20	0.05

CMS: [Scenario2, Scenario1]

L (fb^{-1})	$\gamma\gamma$	WW	ZZ	bb	$\tau\tau$	$Z\gamma$	$\mu\mu$	inv.
300	[6, 12]	[6, 11]	[7, 11]	[11, 14]	[8, 14]	[62, 62]	[40,42]	[17, 28]
3000	[4, 8]	[4, 7]	[4, 7]	[5, 7]	[5, 8]	[20, 24]	[20,24]	[6, 17]

Not with LO κ-language

The SOPHIST view

- *A machine that can measure couplings with limited precision can only claim a discovery of a SM-like Higgs boson*
- *If the same machine can measure couplings that differ significantly from the predicted SM values, then it is possible to rule out the SM Higgs boson at that machine*

Vacuum stability vision

Definition

Trivially: in the absence of NP the LHC-boson makes the universe metastable at $\Lambda \approx 10^{10-12}$ ***GeV***

Various speculations on the meaning of that result are popping out

Precision striking back : **But ... small deviations from SM couplings is a guess based on absence of NP so far with more data the properties of the LHC-boson could get even closer to the SM predictions which is very challenging (more than rushing now to too quick conclusions): deviations may be of the order of the present SM uncertainties**

An induced approach: The *put money where mouth is* approach

- No matter how challenging it may be to see BSM
- Precision Higgs Physics looks now like a must! ✓

❝ Science can only be understood backwards; but it must be lived forwards ❞ (paraphrasing Soren Kierkegaard)

- QUINTESSENTIAL PRECISION: we find ourselves in a *just-so* situation, the vacuum is at the verge or being stable or metastable. A sub-percent change of $\sim$ **1** ***GeV*** in either M_t or M_H is all it takes to tip the scales

The *Missing Guiding Principle* scenario

- Have we lost our motivation (e.g. no guiding principle from naturalness)?
- Maybe yes, maybe no if motivation remains *derive* **EWSB** and/or *compute parameters in a deeper theory*

After all, naturalness is a vague concept and the **SM** is a renormalizable theory

❝ *If one ignores the hierarchy problem it is completely fine and predictive* ❞ (G. Altarelli)

Only when you try to predict **EW** observables from a deeper theory you face naturalness It is plausible to assume that Nature has a way, still hidden to us, to realize *a deeper form of naturalness at a more fundamental level*

Feynmanian versus Wilsonian visions, i.e. Λ cutoff versus scale of NP

$$\mathscr{L}_{\rm ESM} = \mathscr{L}_{\rm SM} + \sum_{n>4}\sum_{i=1}^{N_n} \frac{a_i^n}{\Lambda^{n-4}}\,\mathscr{O}_i^{(d=n)} + \sum_{i=1,2,4} b_i\,\Lambda^i\,\mathscr{O}'_i$$

- SM *not embedded* means $b_{1,2} = 0$, *it's renormalization*!
- SM *embedded* (Wilsonian scenario), b_2 not suppressed by any symmetry
  - $M_{\rm H}$ should be $\mathscr{O}(\Lambda)$ and it is light, thus $\delta M_{\rm H}^2 \sim \Lambda^2$
  - $M_{\rm H} \approx 125\ GeV$ which means $\Lambda \approx 1\ TeV$ (which doesn't seem to be the case) or FINE TUNING (**not a theorem!**)

QFT: infinities, renormalization, predictions. Status OK (but Landau poles are there and, possibly, instability is present), many things remain unexplained. **SM** is **QFT**, as it is **QED** (not embedded into **SM**)

QFT with embedding : requires a cutoff scale for the embedding, the physics of that scale is unknown . Keywords are triviality and vacuum stability

Lindner CLASSIFICATION :

- $M_H = 125{-}126$ ***GeV*** $\rightarrow$ instability $\rightarrow$ new physics
- $M_H = 126{-}157$ ***GeV*** SM ... non-minimal Susy perfect
- $M_H > 157$ ***GeV*** real BSM required

Now we know where we stand ✓

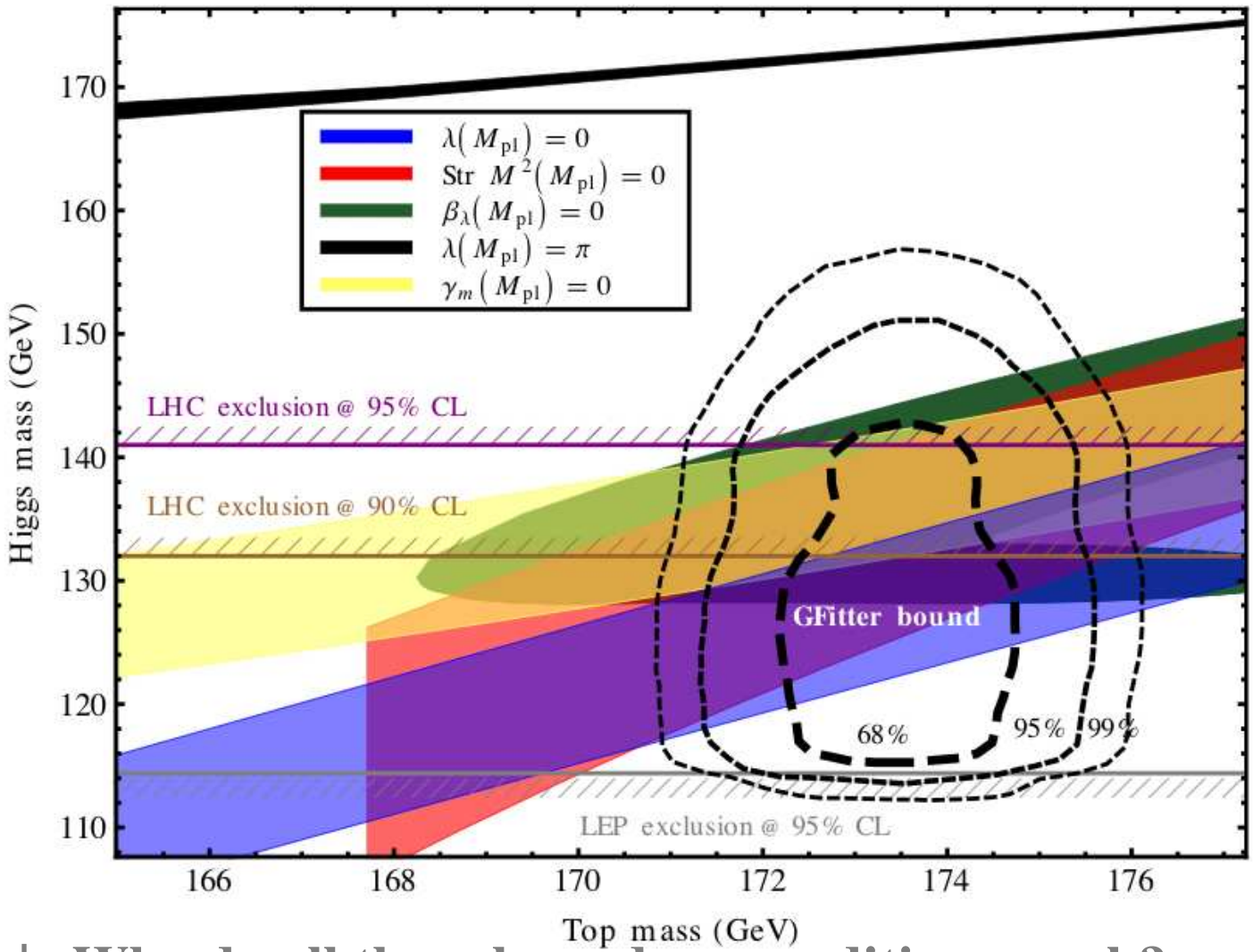
Why all of a sudden questions like *a special value of* $\boldsymbol{\lambda}$ *at* $\boldsymbol{M_{\text{plank}}}$*?* are becoming a popular tune?

$$V = \frac{1}{4}\,\lambda(\mu)\,\mathrm{H}^4, \qquad \lambda_0 = \frac{1}{4}\,\frac{M_{\mathrm{H}}^2}{v^2}$$

Conceivable special scenarios

- Vacuum stability, $\boldsymbol{\lambda\left(M_{\text{plank}}\right) = 0}$
- vanishing of $\boldsymbol{\beta}$-function, $\boldsymbol{\beta_\lambda\left(M_{\text{plank}}\right) = 0}$
- the *Veltman* condition (cancellation of quadratic divergencies)

From M. Lindner talk at SCALARS 2013



m_H

!

exc

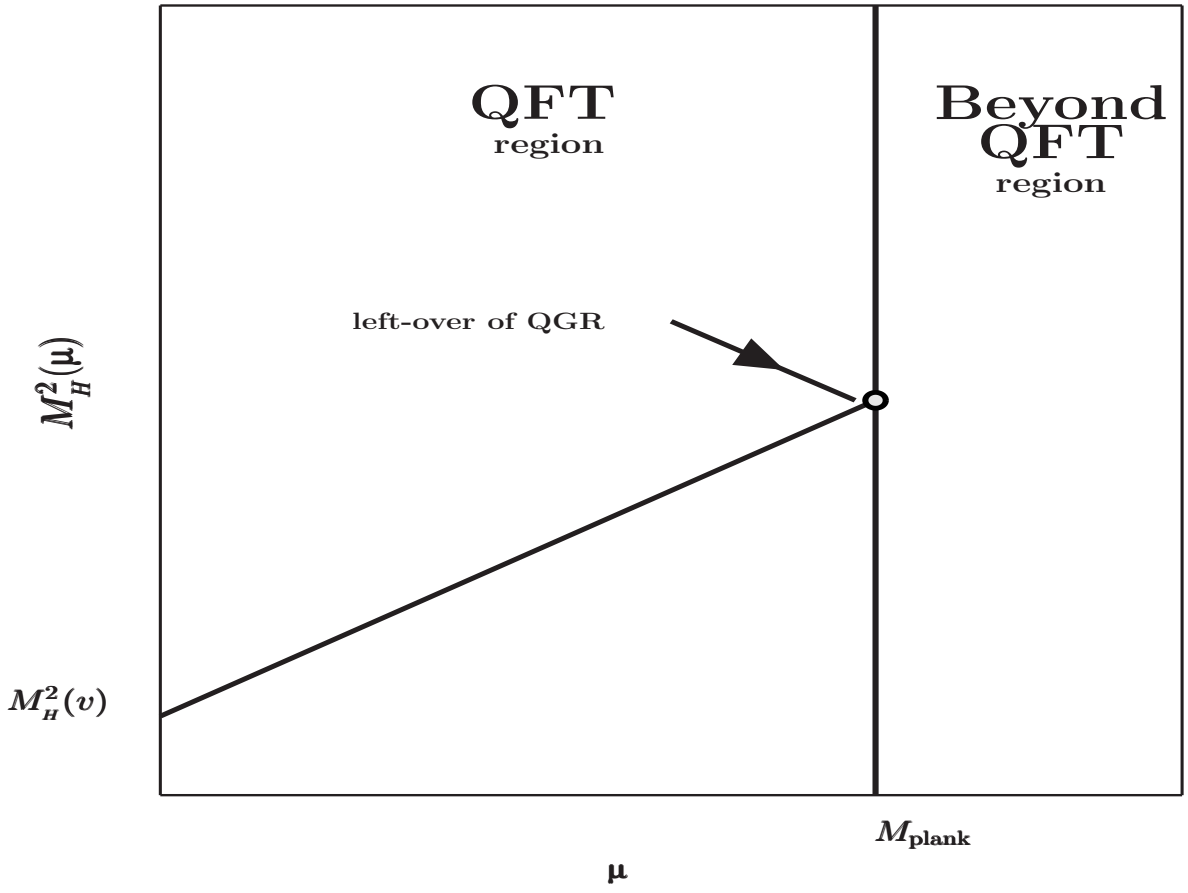
- ! **Why do all these boundary conditions work?**
  - suppression factors compared to random choice = O(1

The most interesting question: *is the Higgs potential at* M_{plank} *flat? Why?*

- ⇝ V flat means no Higgs self-interaction
- ⇝ Is the **SM** *directly embedded* into gravity ...?

In this case

- We do not have a renormalizable **QFT** of gravity
- we need to move beyond QFT ! *It means new non-QFT Plank-scale concepts* !


QFT
region
Beyond
QFT
region
left-over of QGR
$M_H^2(\mu)$
$M_H^2(v)$
M_{plank}
μ

The *Set your preferences* scenario

1. New **QFT**
2. Beyond **QFT**

The second scenario is relatively new and avoids hierarchy problem by shifting it to the unknown region, the first is the traditional one where one plays with

- more representations, new groups, inclusion of **XXXSSM**
- and ... runs into hierarchy problem
- or set NP-scale above M_{plank} ...

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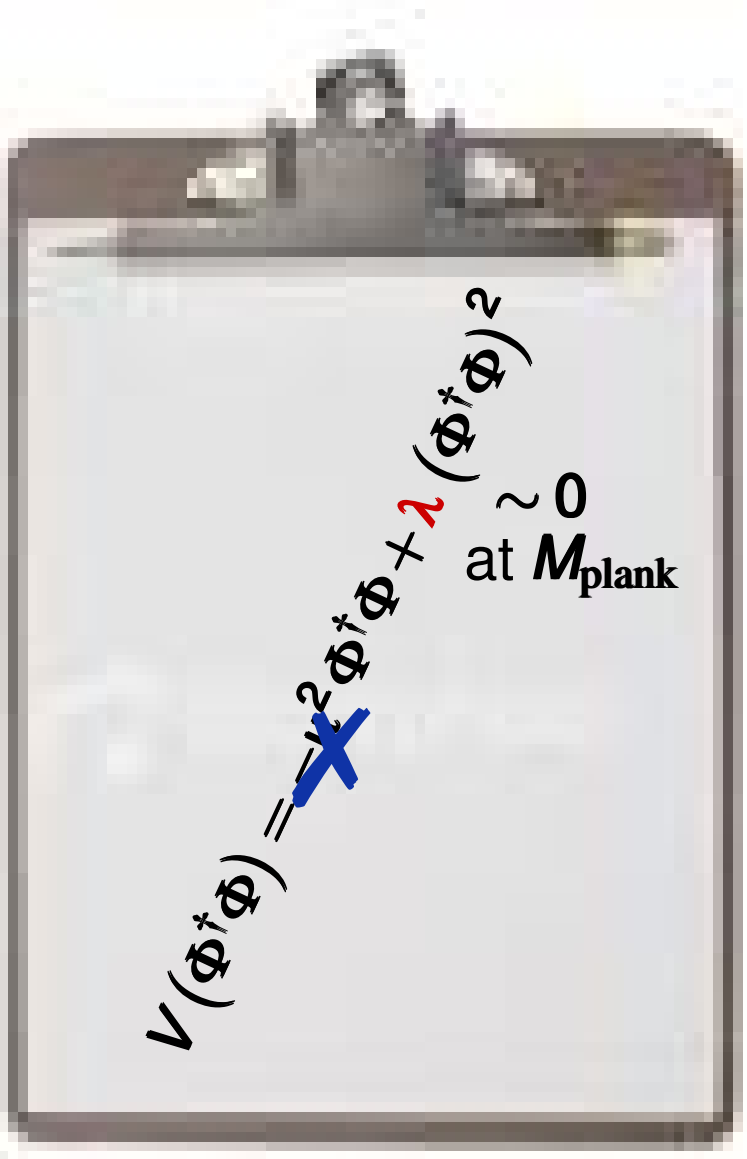
The Try something new *conformal* vision



Almost CS!

broken CS?

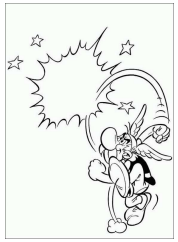
$\mu = 0$ + Coleman-Weinberg? ✗

M_H too low (from CW), too high (from Veltman condition)

Perturbatively natural conformal extension?

Lindner, Sannino, . . .

the Phase Transition vision (F.Jegerlehner)

it is based on 

- *is the Higgs potential stable up to the Planck scale or not?*
- *Does the coefficient of the term quadratic in* Λ *have a zero below* M_{plank}*?*

Results are very sensitive to the top Yukawa coupling and, therefore, to the value of M_t see G. Degrassi talk, see also

- Higgs mass and vacuum stability in the Standard Model at NNLO, G. Degrassi et al
- Investigating the near-criticality of the Higgs boson, D. Buttazzo et al

Conjecture

THE QUADRATIC UV TERM TRIGGERS A PHASE TRANSITION

Consequence:

- The quadratic divergence *problem* is the solution and not the problem of the SM
- The quadratically enhanced positive Higgs potential mass term which must have existed in the very early universe, before the PT took place after cooling down, just means that the SM predicts inflation, and not only that, it predicts it to have the properties (equation of state, Gaussianity, primordial fluctuation spectral index) extracted from the analysis of the cosmic microwave background radiation
- COMPARE **to** orthodoxy!

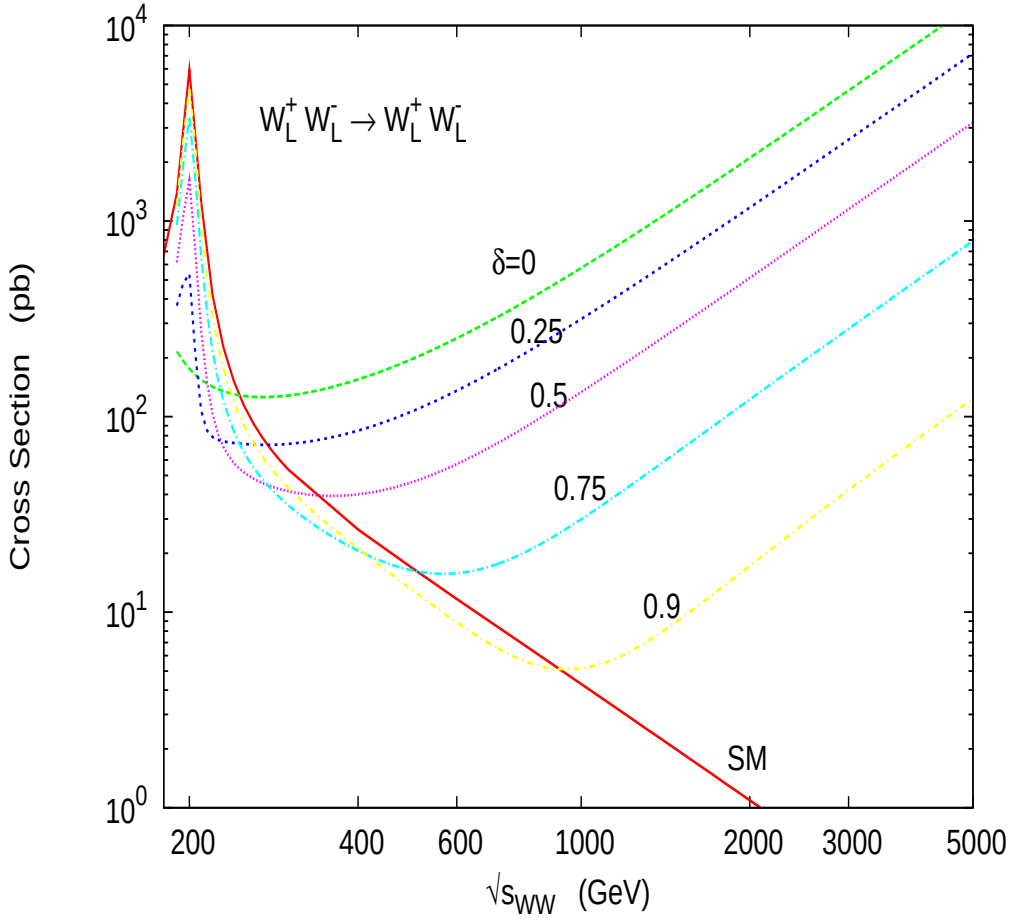
Emphasising Degrassi talk

- **The M_t problem:** λ *always positive*? Only for $M_t \approx 171$ *GeV*, for $mt = 173$ *GeV* one has $\lambda < 0$ around $\Lambda \sim 10^{10}$ *GeV*
- **Conclusion:** stability or metastability, the **SM** is extendable up to M_{plank}
- **The $\lambda < 0$ problem** :
  - **if λ** gets negative around some scale the SM looses any sense beyond that scale
  - The effective potential is a complicated function of the scale that has a minimum; the only question is **is this minimum lower than the EW one?**
- **The "quadratic divergencies" problem** : is Λ^2 the same for all loops (scalars, fermions, vectors)? They should be seen as poles at $d = 4 - 2/n_L$ and there is no complete agreement in the literature **(see D.R.T Jones arXiv:1309.7335)**

The where to put money vision

If the LHC boson alone contributes to **EWSB** $\mathbf{V_L V_L}$ -scattering does not grow at high energies

- New Physics also means that the LH boson is not alone but
- NP non-observability at **1** ***TeV*** tells us that the rest is heavy. *Then the scattering could get strong for a range of energies, until the high-energy UV physics starts unitarizing*
- LHC experiments can/could reveal this interesting possibility
- Suppose the Higgs coupling to $\mathbf{WW}$ is $\sqrt{\boldsymbol{\delta}}$ of the SM value ☛



Cheung, Chiang, Yuan

Partially-strong scattering: THDM

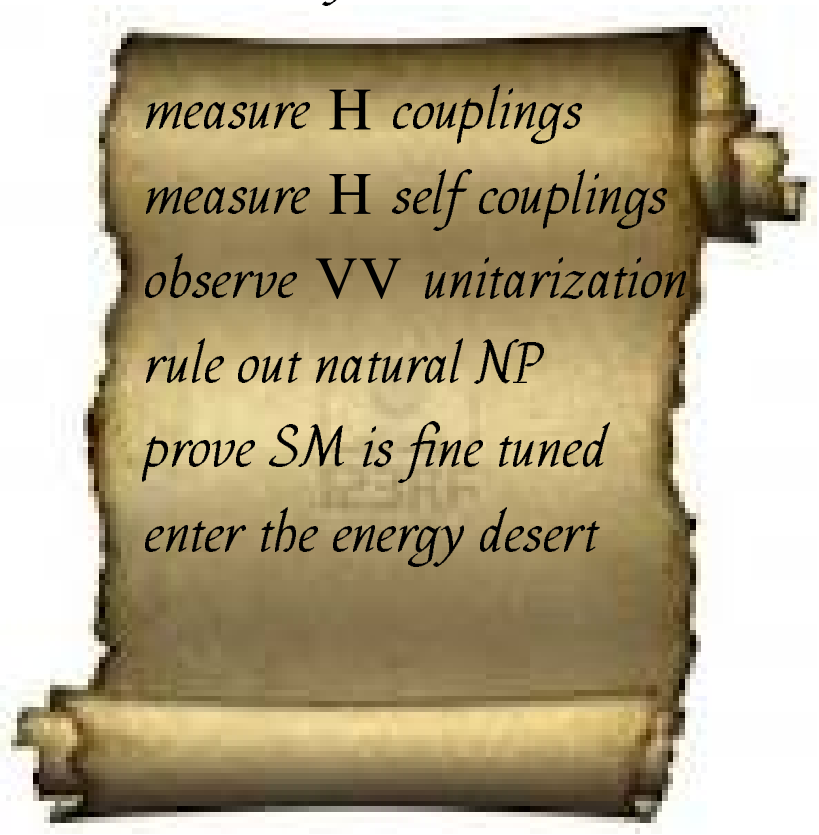
$$g_{hVV} = \sin(\beta - \alpha)\, g^{SM}_{H^0VV} \qquad g_{HVV} = \cos(\beta - \alpha)\, g^{SM}_{H^0VV}$$

- Energy growing behavior tamed above M_H
- growing behavior expected *if there is space enough between* M_h *and* M_H

Warning ☛

the measurement of the VV scattering at the Atlas and CMS experiment is very challenging and statistically limited. Experimentally, all final states can be studied; while the fully leptonic ones have very little background, but a very small statistics, the semi-leptonic ones suffer from a very large background coming from $t-t$, VV + jets , V + jets production

The Lost Book of Nostradamus



Conclusions

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Conclusions

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- Invest the remaining **50%** in quantification of the concept of naturalness and in searching for new models
- Are you Popper-like (progress is through testing falsifiable ideas) or Kuhn-like (progress is through producing results that fit in with the established view point)?
- ❝ A new scientific truth does not triumph by convincing its opponents and making them see the light, but rather because its opponents eventually die, and a new generation grows up that is familiar with it ❞

Max Planck, Scientific Autobiography and Other Papers

HC 2014

See you all in Torino for HC14

Thanks for your attention