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OPENING SYMPOSIUM

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Implications of the Higgs Discovery

G.F. Giudice

The discovery of the Higgs boson is one of the primary goals of the LHC. What will be the implications of this discovery for our understanding of the physical world?

The success of our understanding of physical laws in terms of elementary particles is based on the concepts of

- Symmetry
- Effective theories

Central role of mass scales (energy at which an effective description is replaced by a new theory)

$\boxed{\Lambda_{QCD}^{-1}} \approx 10^{-15}\,\mathrm{m} \approx (200\,\mathrm{MeV})^{-1}$ confinement, chiral symmetry breaking, quark-hadron transition

$\boxed{G_F^{1/2}} \approx 10^{-18}\,\mathrm{m} \approx (200\,\mathrm{GeV})^{-1}$ electroweak breaking, elementary particle masses

? $\boxed{m_\nu G_F} \approx 10^{-32}\,\mathrm{m} \approx (2\times 10^{16}\,\mathrm{GeV})^{-1}$ neutrino masses, grand unification?, proton decay?

$\boxed{G_N^{1/2}} \approx 10^{-35}\,\mathrm{m} \approx (2\times 10^{19}\,\mathrm{GeV})^{-1}$ quantum gravity, superunification?

New phenomena are associated with each scale

The weak scale G_F^{-1} entered physics during the cloudy Parisian days of Feb 26 and 27, 1896, when Becquerel studied the phosphorescence properties of some uranium salts

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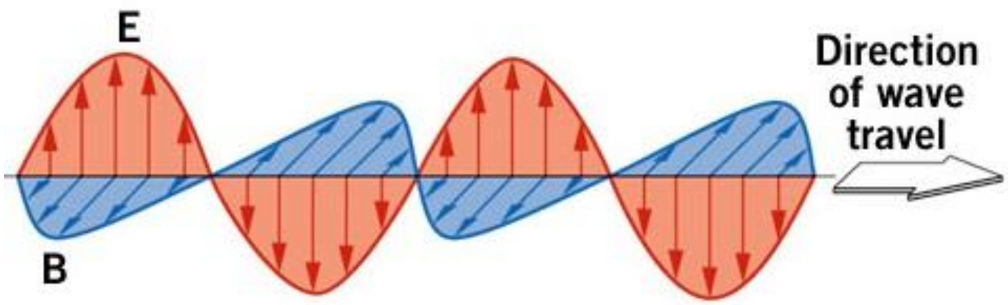
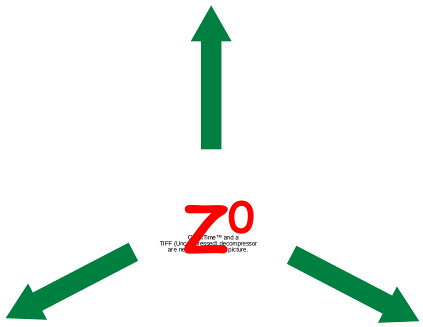
The mechanism generating the weak scale will finally be fully unveiled by the LHC

The problem:

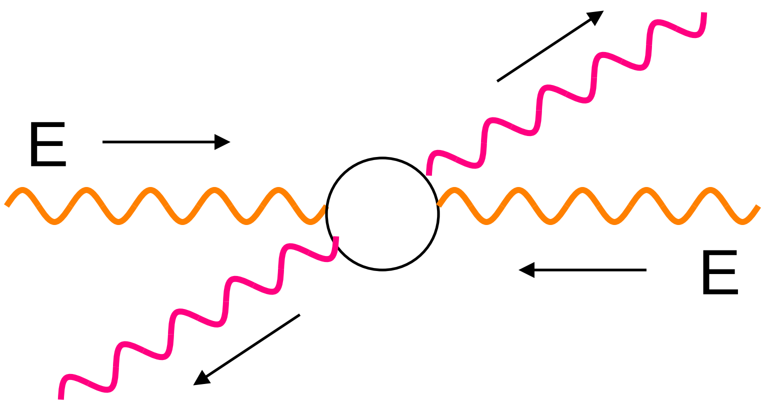
While massless photons have 2 polarization states,





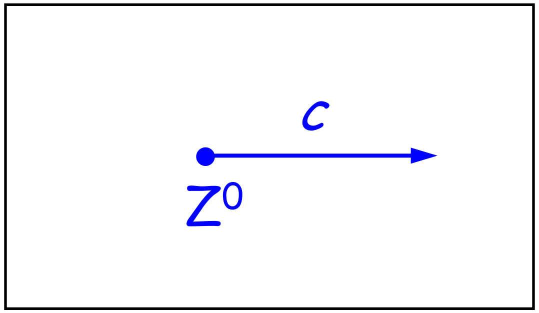
massive spin-1 particles (Z^0,$W^{\pm}$) have 3

Scattering of longitudinal modes grows with E
$\Rightarrow$ nonsense at E > TeV

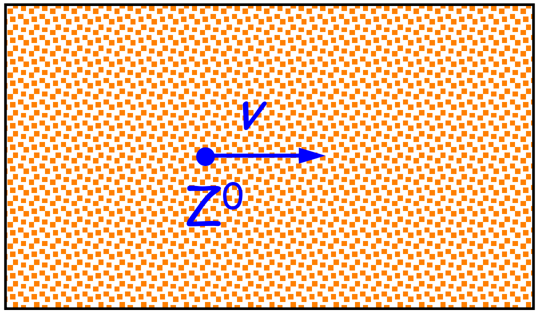


Description of massive Z^0 and $W^{\pm}$ breaks down at TeV
$\Rightarrow$ solution within reach of the LHC

The Higgs mechanism is a clever solution:
it modifies the properties of the vacuum



empty space



Higgs-filled space

Large distances: propagation of Z^0 and $W^{\pm}$ is affected
$\Rightarrow$ energy-momentum relation of massive particle

Small distances: negligible effect of dilute "Higgs fluid"
$\Rightarrow$ effective massless spin-1 at high energies

LHC: What causes these non-trivial properties of the vacuum?

Understanding “nothing” has a long history

Western thought was influenced by Artistotle’s proof that vacuum cannot exist in nature

“Any motion will come to a standstill unless some external force keeps driving it”

In empty space, why should a body stop in one place rather than another?

Absurd!

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“Natural motions (without external agent) make heavy elements (earth, water) fall down and light elements (air, fire) go up”

How could natural motions exist in empty space?

The principle of Horror Vacui: Nature will work in a way to prevent the appearance of vacuum

Experimental proof of the Horror Vacui principle

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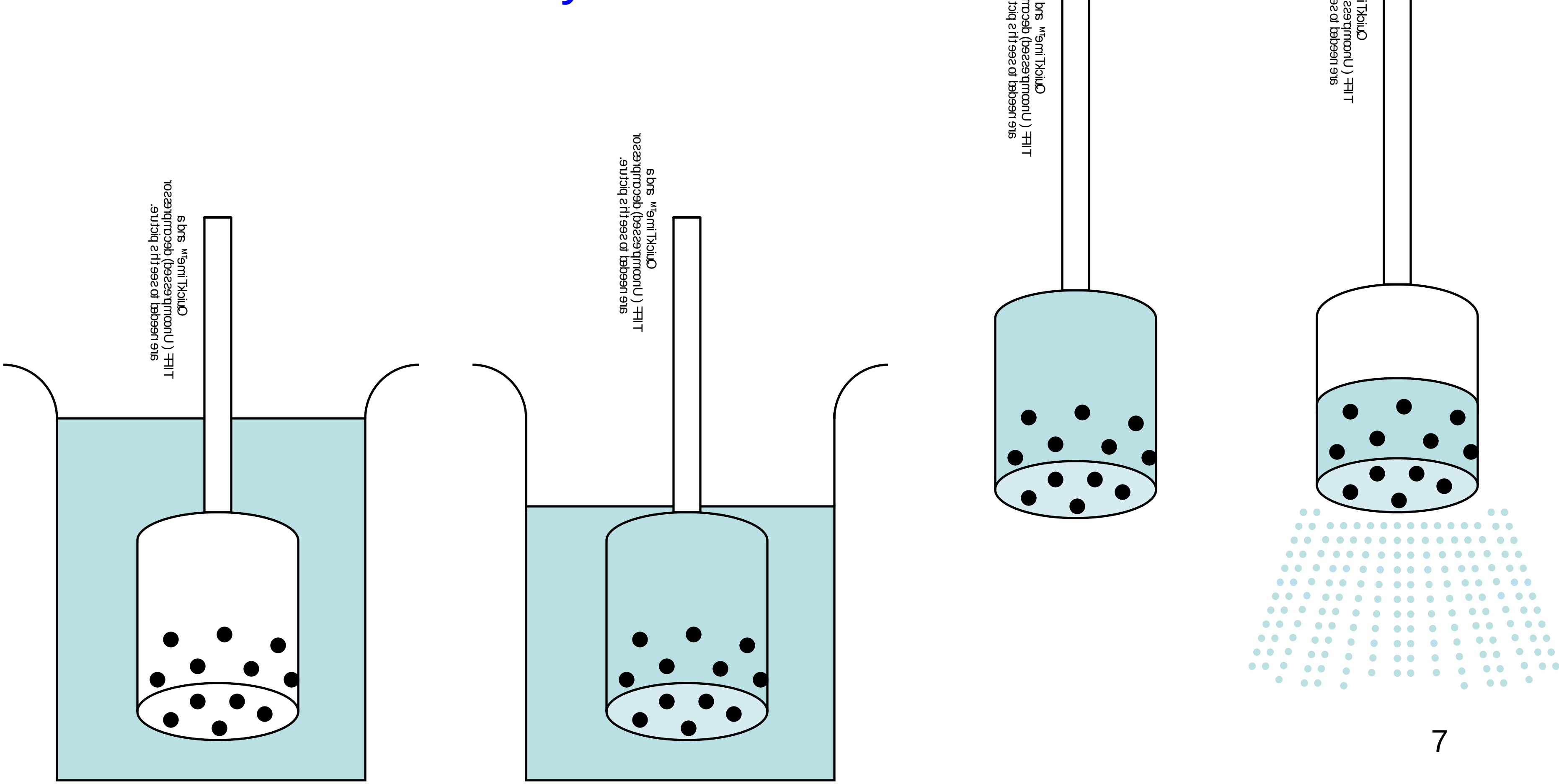
Empedocles'
Hydra



It took Torricelli and Pascal to understand that the effect is due to air pressure

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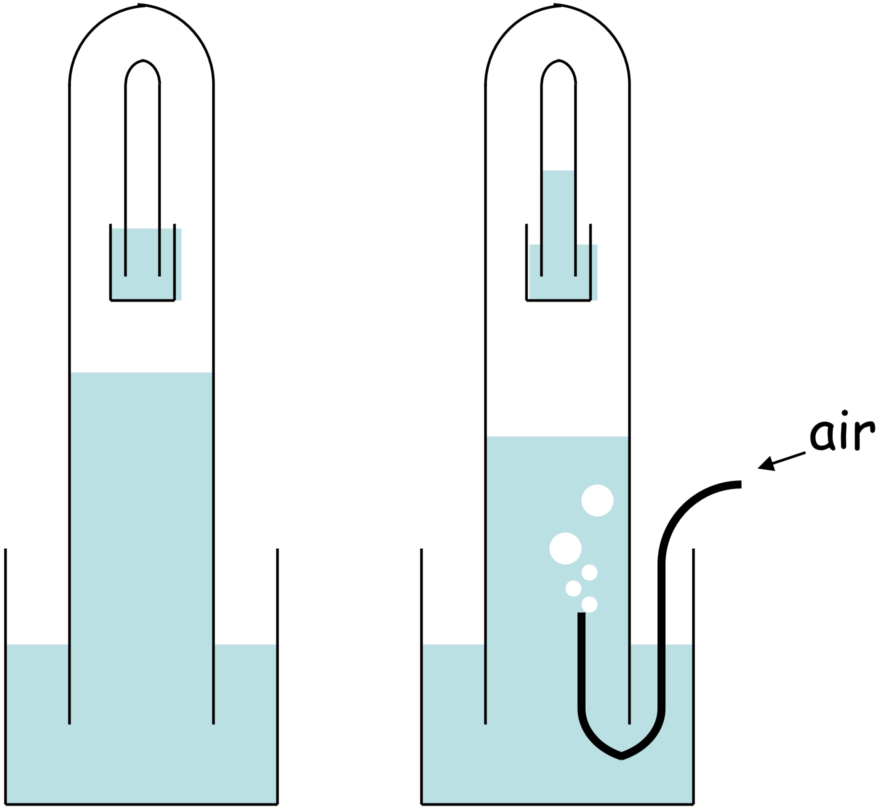


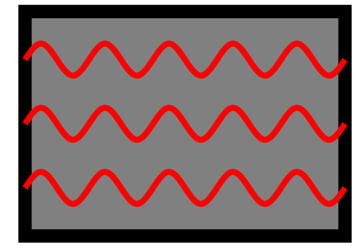
Evangelista Torricelli's
experiment (1644)

Blaise Pascal's
vide dans le vide

Does nature abhor void after all?

Even if we remove all matter from space, we do not get “nothing”

The walls of the container emit blackbody radiation



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Because of Heisenberg’s principle, virtual particles are produced out of nothing

Physical measurable effect: Casimir force

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LHC:

At $T < 10^{15}$ K, the vacuum undergoes a phase transition and generates the “Higgs fluid” that affects particle production

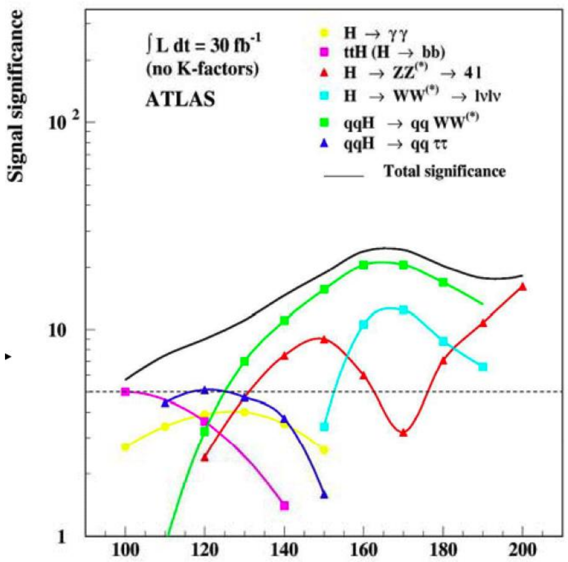
Measure the quantum excitation associated with the "Higgs fluid"

Karl Jakobs

Goals of the Higgs' hunt:

- Verify that particle masses are due to their dragging inside the "Higgs fluid"

Higgs–*p* coupling $\propto m_p$



- Measure m_H: the dragging of the Higgs from itself

- Identify the force that induces the Higgs condensate: weakly-interacting, strongly interacting, or no Higgs?

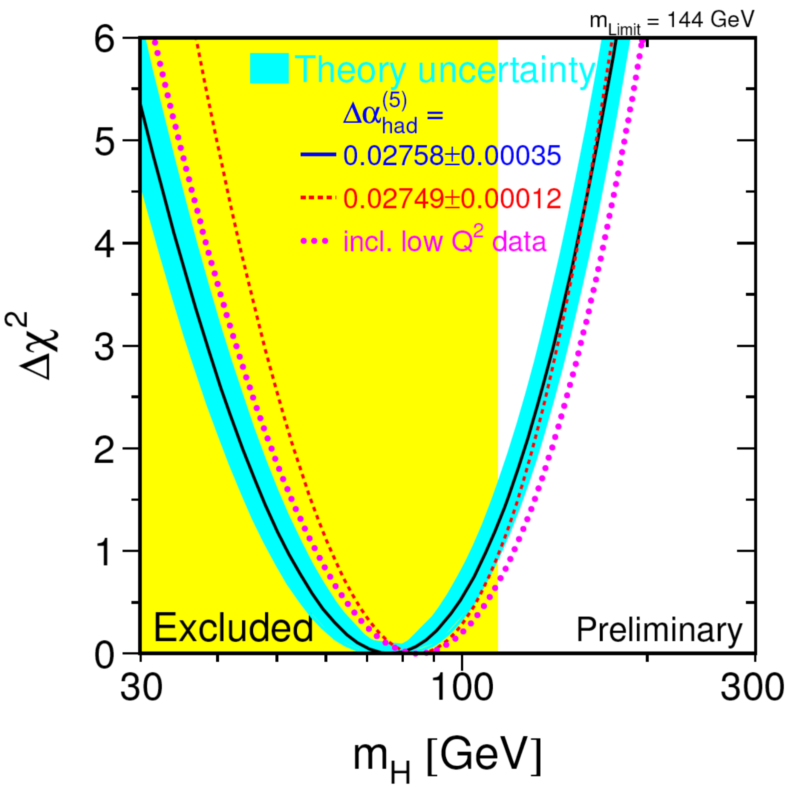
THE HIGGS MASS

In the SM, it is the only remaining unknown parameter

LEP has given us info:

Lower limit m_H > 114.4 GeV (95% CL)

Upper limit?



Preferred value $m_H = 76^{+33}_{-24}\,\mathrm{GeV}$

Upper limit $m_H < 144\,\mathrm{GeV}$ (95% CL)

including direct limit of $114\,\mathrm{GeV}$:

$m_H < 182\,\mathrm{GeV}$ (95% CL)

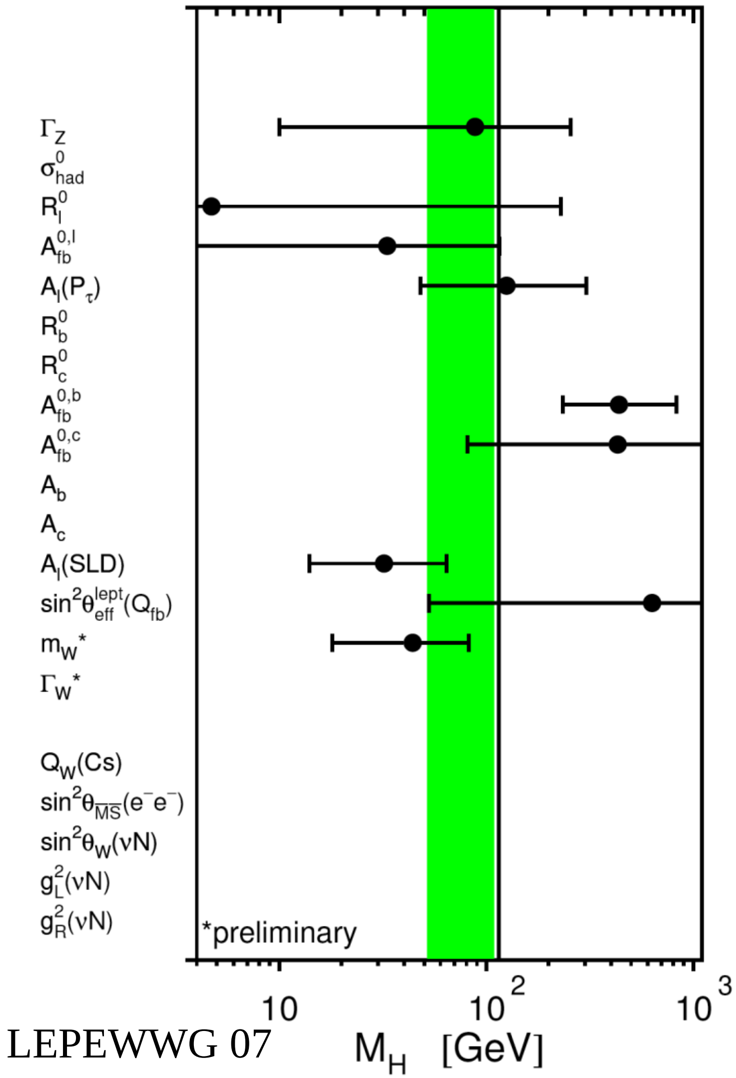
LEPEWWG 07

The two best measurements of $\sin^2\theta_W$ do not agree

$$A_{fb}^{0,b} \Rightarrow m_H = (230-800)\,\mathrm{GeV}$$

$$A_\ell(\mathrm{SLD}) \Rightarrow m_H = (13-65)\,\mathrm{GeV}$$

This makes the argument for a light Higgs less compelling



The possibility of a heavy Higgs or no Higgs is still open

Actually, both the lower and upper limits on m_H can be violated for certain modifications of the SM

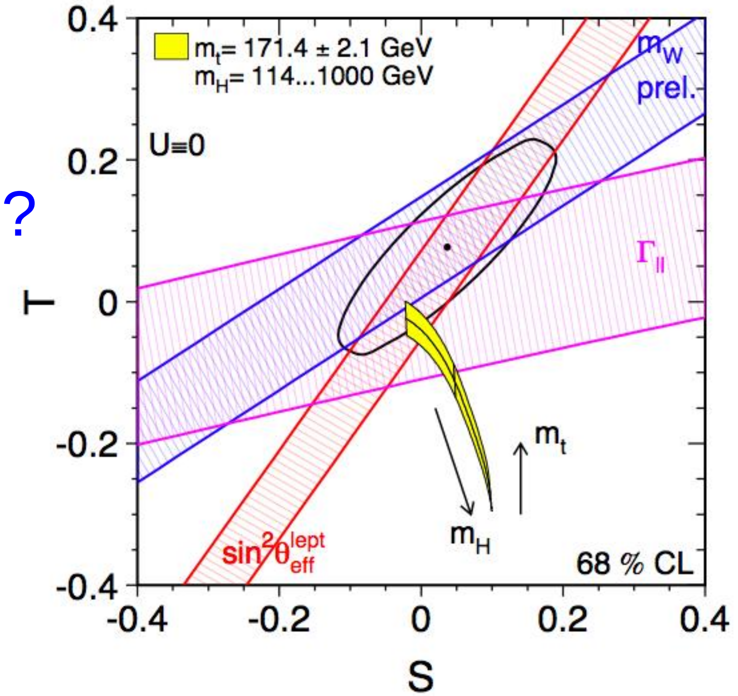
Evading m_H upper bound from EWPT?

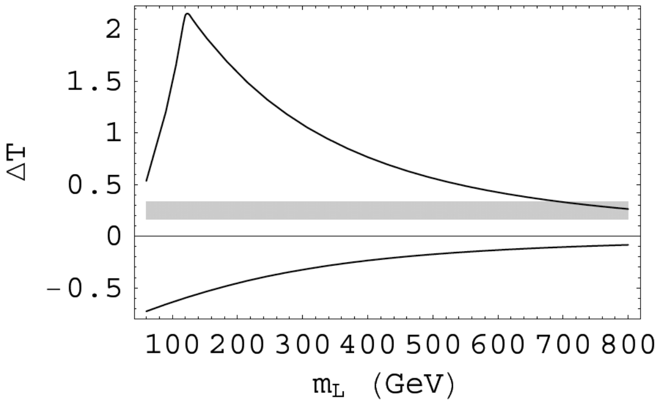
Requires new physics with ΔT=0.2–0.3 and ΔS small

$$S \to H^+ W_{\mu\nu} H B^{\mu\nu}$$

$$T \to H^+ D_\mu H H^+ D^\mu H$$

It can be obtained with a second Higgs doublet with no vev and no coupling to fermions

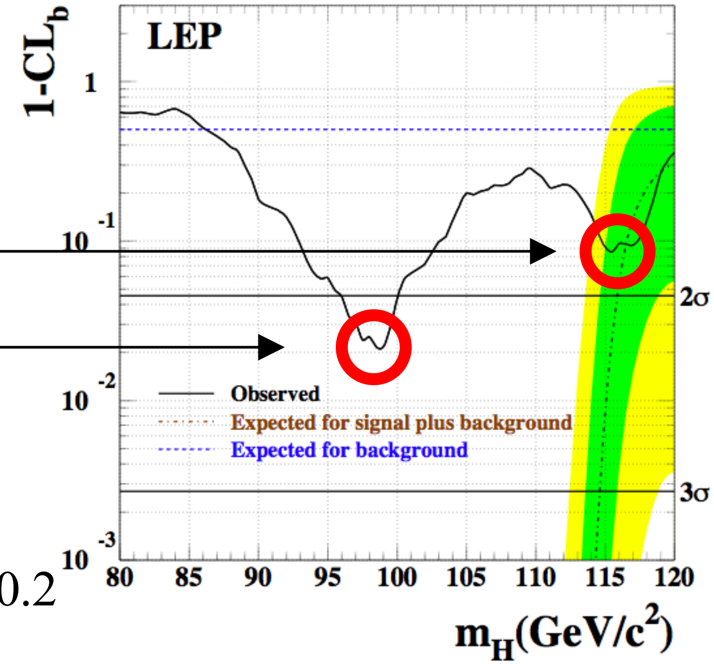




- Evading m_H lower bound from LEP?

Controversial signal at 115 GeV

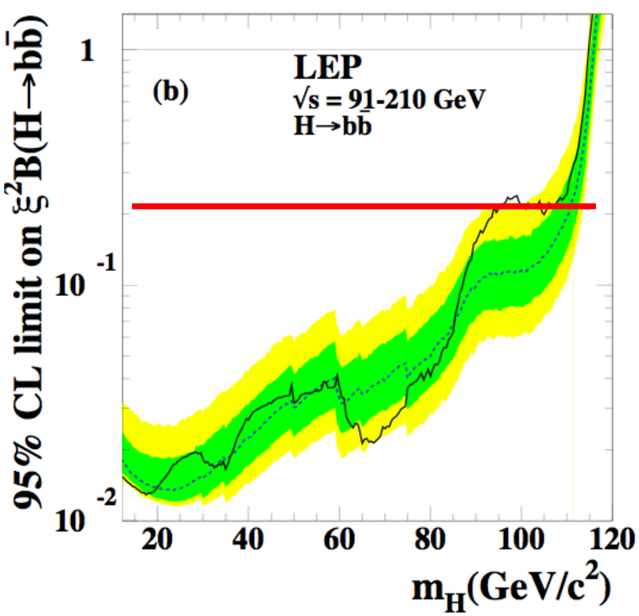
2.3σ excess at 98 GeV



Excess at 100 GeV requires $\left(\dfrac{g_{hZZ}}{g_{hZZ}^{(\mathrm{SM})}}\right)^2$ $B(h \to b\bar{b}) \approx 0.2$

New decay modes (new particles)

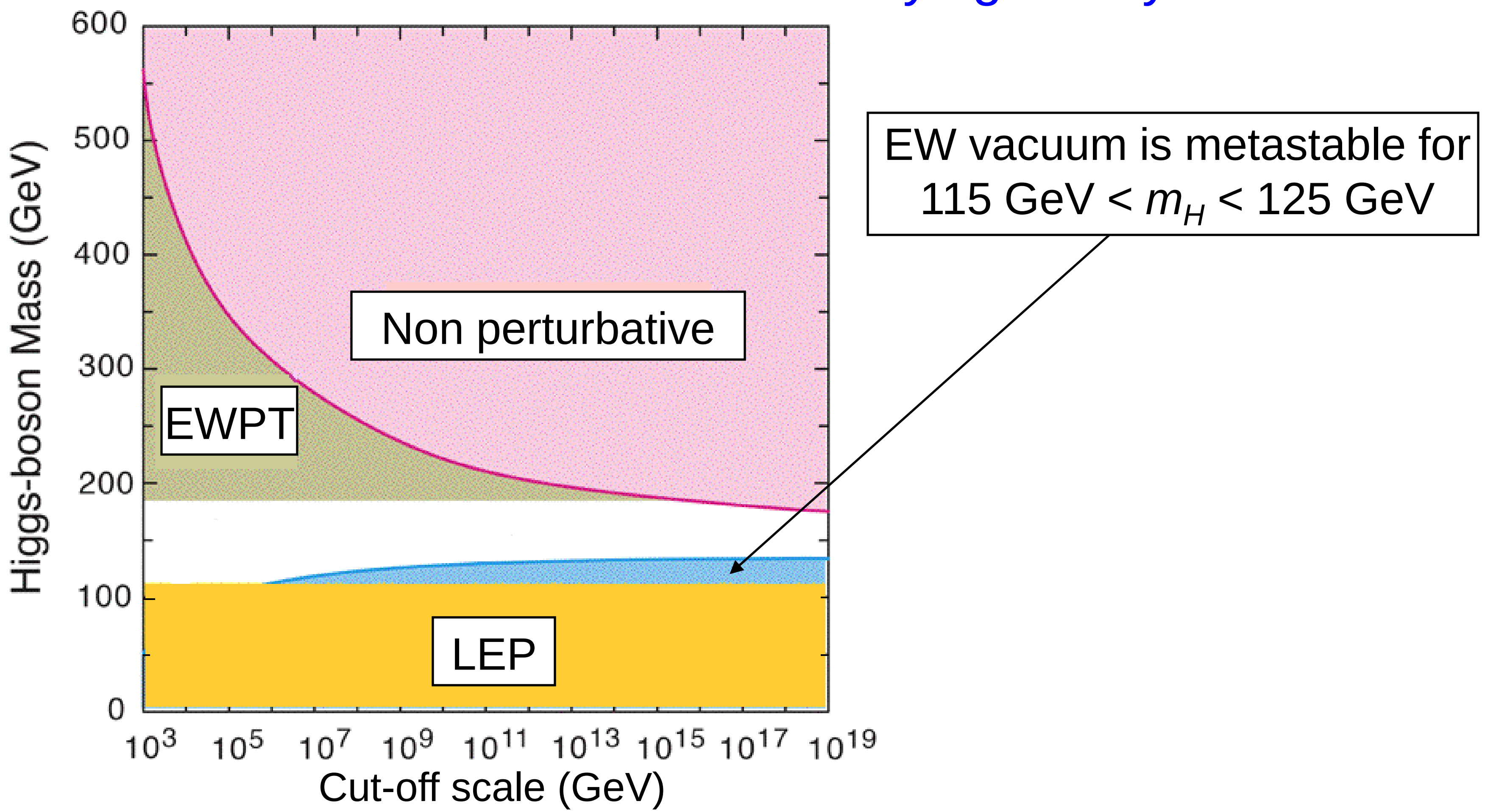
Change Higgs nature (mixing with other states)



Limits on unconventional decay modes

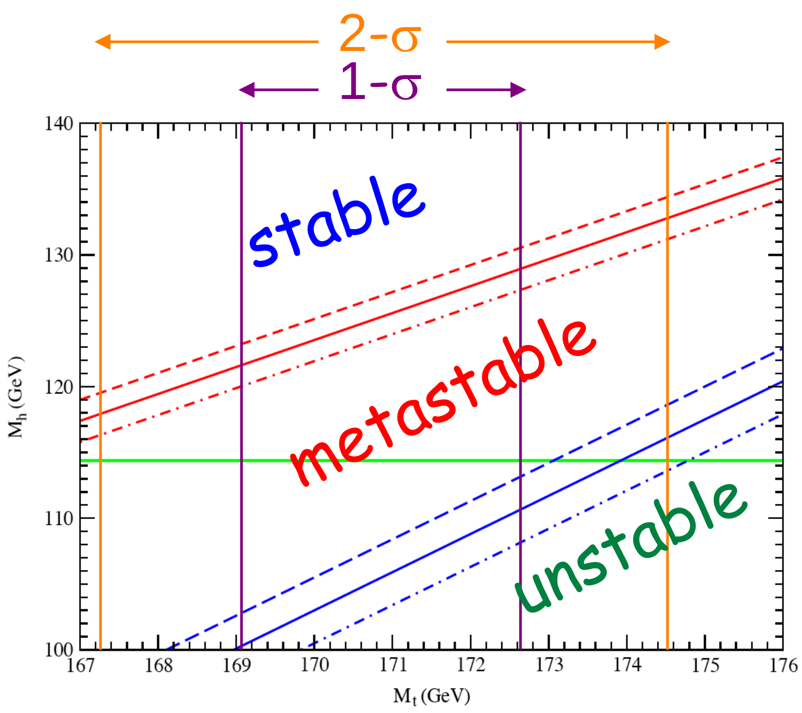
$h \to \gamma\gamma$	$m_h > 117\mathrm{GeV}$
$h \to 2$ jets	$m_h > 113\mathrm{GeV}$
$h \to$ invisible	$m_h > 114\mathrm{GeV}$
$h \to b\bar{b}b\bar{b}$	$m_h > 110\mathrm{GeV}$
$h \to \tau^+\tau^-\tau^+\tau^-$	$m_h > 87\mathrm{GeV}$
$h \to$ anything	$m_h > 82\mathrm{GeV}$ OPAL

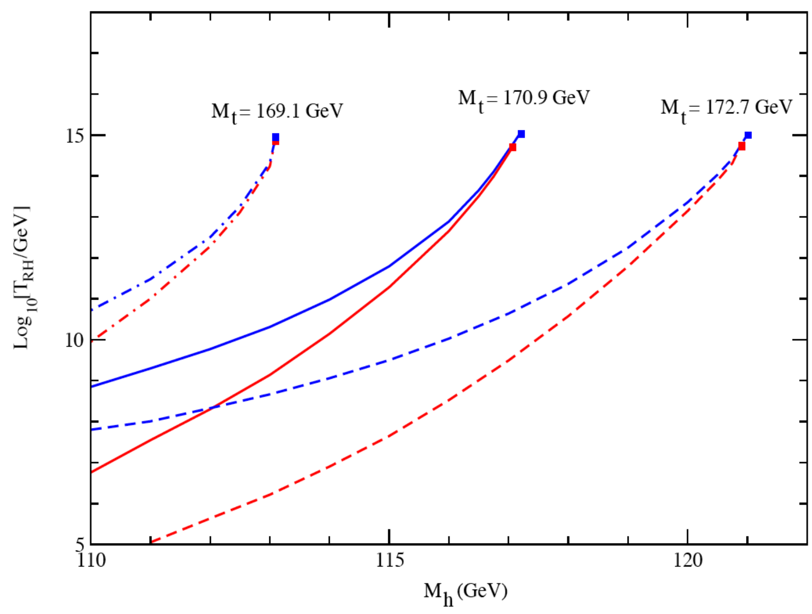
The Higgs mass carries important information on the underlying theory



m_H > 180 GeV: new effects in EWPT? Higgs is a composite particle?
115 GeV < m_H < 125 GeV: metastable Universe?
125 GeV < m_H < 180 GeV: SM valid up to GUT or Planck scale?

The Higgs mass may carry information relevant for cosmology





SM: upper bound on T_{RH} and H_I in metastability region

SUSY: SI scattering rate of DM particles

New Theories: strength of first-order EW phase transition no mixing ($\tilde{m}_t = \mathrm{TeV}$): $m_H < 112\mathrm{GeV}$

gauge med ($\tilde{m}_t = \mathrm{TeV}$): $m_H < 115\mathrm{GeV}$

max mixing ($\tilde{m}_t = \mathrm{TeV}$): $m_H < 128\mathrm{GeV}$

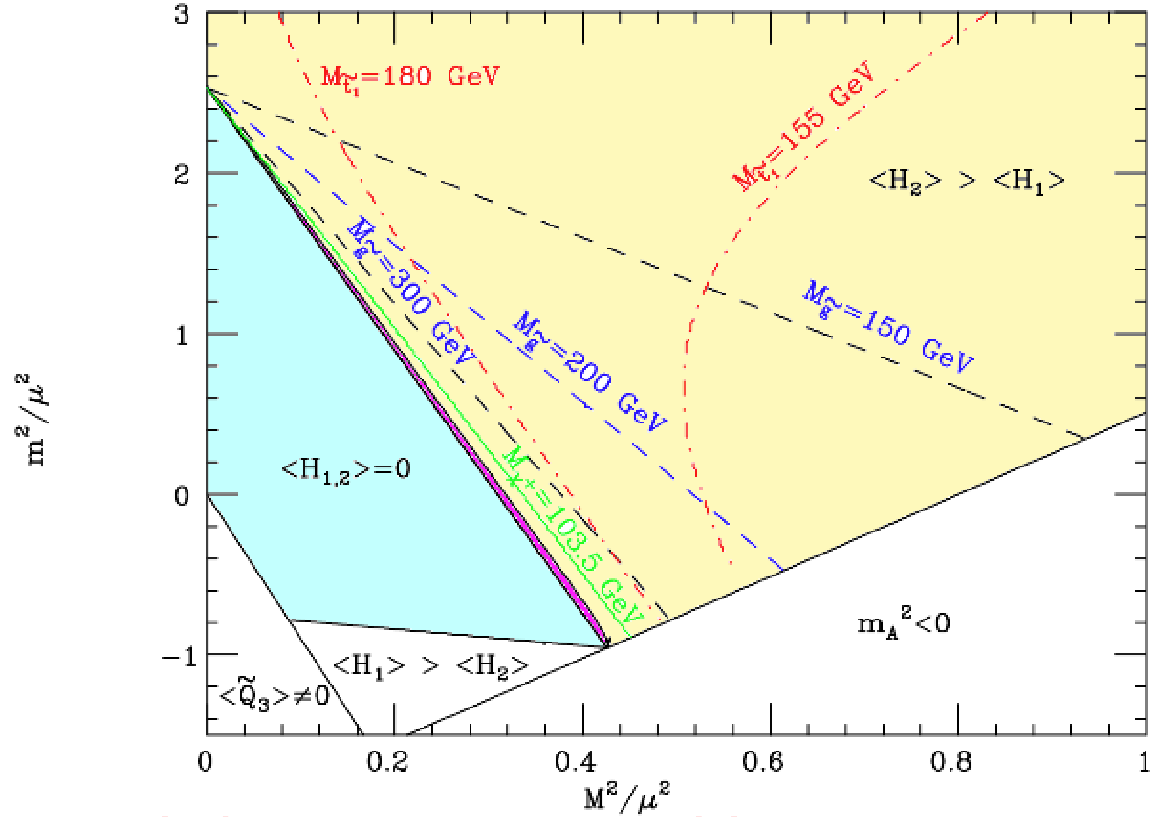
split susy ($\tilde{m} = 10^7\,\mathrm{GeV}$): $m_H < 145\mathrm{GeV}$

λ perturb. up to $10^7\,\mathrm{GeV}$: $m_H < 150\mathrm{GeV}$

The Higgs mass is a key element of most new EW theories

E.g.: low-energy supersymmetry

Bad luck, missing ingredient, or wrong track?



Measurement of m_H will be a powerful guide for model building of new theories

Is the Higgs elementary or composite?

Determine the nature of the force that breaks EW

Elementary
- SM (with $m_H < 190$ GeV)
- SUSY (H,Q,L are all chiral superfields)

Composite: Higgs is a light remnant of a strong force
- pseudoGoldstone
- Little Higgs
- Gauge-Higgs unification
- Holographic Higgs
- ….

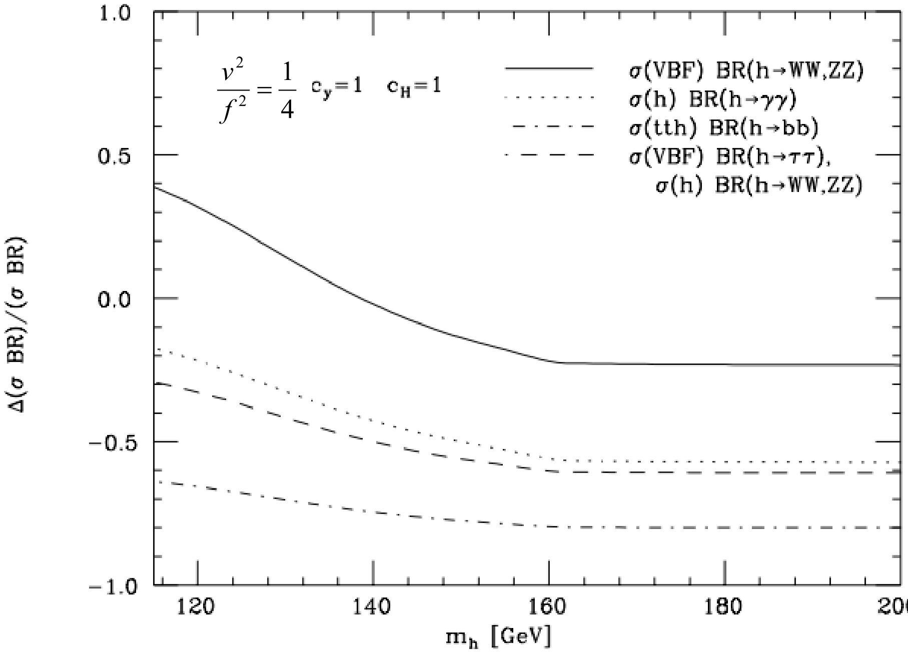
Signatures at LHC? New resonances, *W',Z',t',* KK excitations

Distinctive model-independent features of compositeness at the LHC in Higgs interactions

Describe Higgs with a σ-model deformed by gauge and Yukawa interactions

Specific patterns of modified Higgs couplings

$$\sqrt{1+c\frac{v^2}{f^2}}$$



Deviations from SM Higgs couplings can test v^2 / f^2 up to

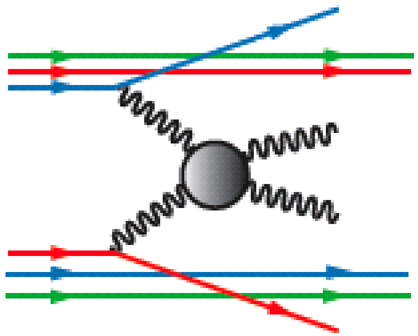
LHC 20–40 %

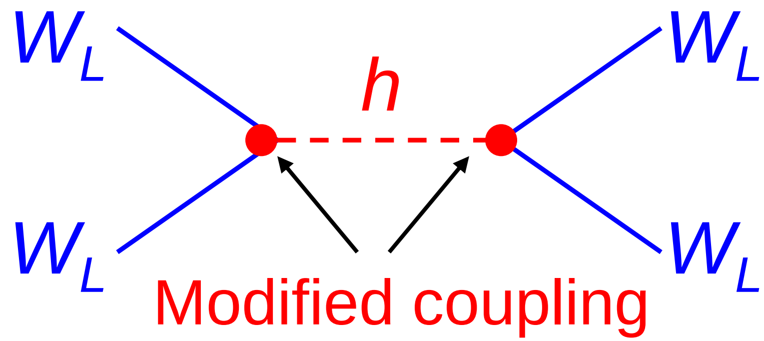
SLHC 10 %

ILC 1 % $\Rightarrow 4\pi f$ = 30 TeV

Genuine signal of Higgs compositeness at high energies

In spite of light Higgs, longitudinal gauge-boson scattering amplitude violates unitarity at high energies





$$\sigma(pp \to V_L V_L' X) = \frac{v^4}{f^4}\,\sigma(pp \to V_L V_L' X)_{\not{H}}$$

$V_L V_L$ scattering is an important channel, even for light Higgs

The Higgs discovery will explain the mechanism of ~~EW~~,
but it will also open new questions

- Quarks, leptons, gauge bosons are neatly arranged in symmetric and repetitive structures. And the Higgs?

- The "Higgs fluid" gives a contribution to the energy density of the universe 10^{56} times too large. Has gravity anything to do with EW breaking?

- The puzzle of the hierarchy problem

John Ellis

What if the Higgs is NOT discovered?

Surprising result, but exciting prospect for theorists

global $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ broken to $SU(2)_{L+R} \times U(1)_{B-L}$

3 Goldstones

local $SU(2)_L \times U(1)_Y$ broken to $U(1)_Q$

No Higgs, but new phenomena that unitarize $V_L V_L$ scattering
(to be studied by LHC with W^+W^- at large invariant mass)

- Technicolor
- 5-d gauge theory

Breakdown of unitarity:

$$4\,d \quad \Rightarrow \quad \Lambda \approx \frac{4\pi m_W}{g} \approx \mathrm{TeV}$$

$$5\,d \quad \Rightarrow \quad \Lambda \approx \frac{24\pi^3}{g_5^2} \approx \frac{12\pi^2 m_W}{g^2} \approx 10\ \mathrm{TeV}$$

The gauge KK modes delay unitarity violation

CONCLUSIONS

• Discovering the Higgs is not *just* finding a new particle: it is unveiling the phenomenon that gives rise to a fundamental scale in physics

• The measurement of Higgs mass and properties will bring new information about possible new theories underlying the SM

• The Higgs discovery will be the final chapter in the history of the SM, but it will also open new questions, some of which will be addressed by the LHC