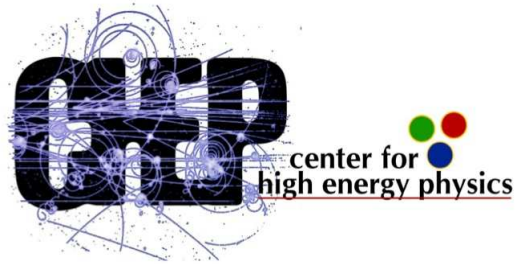
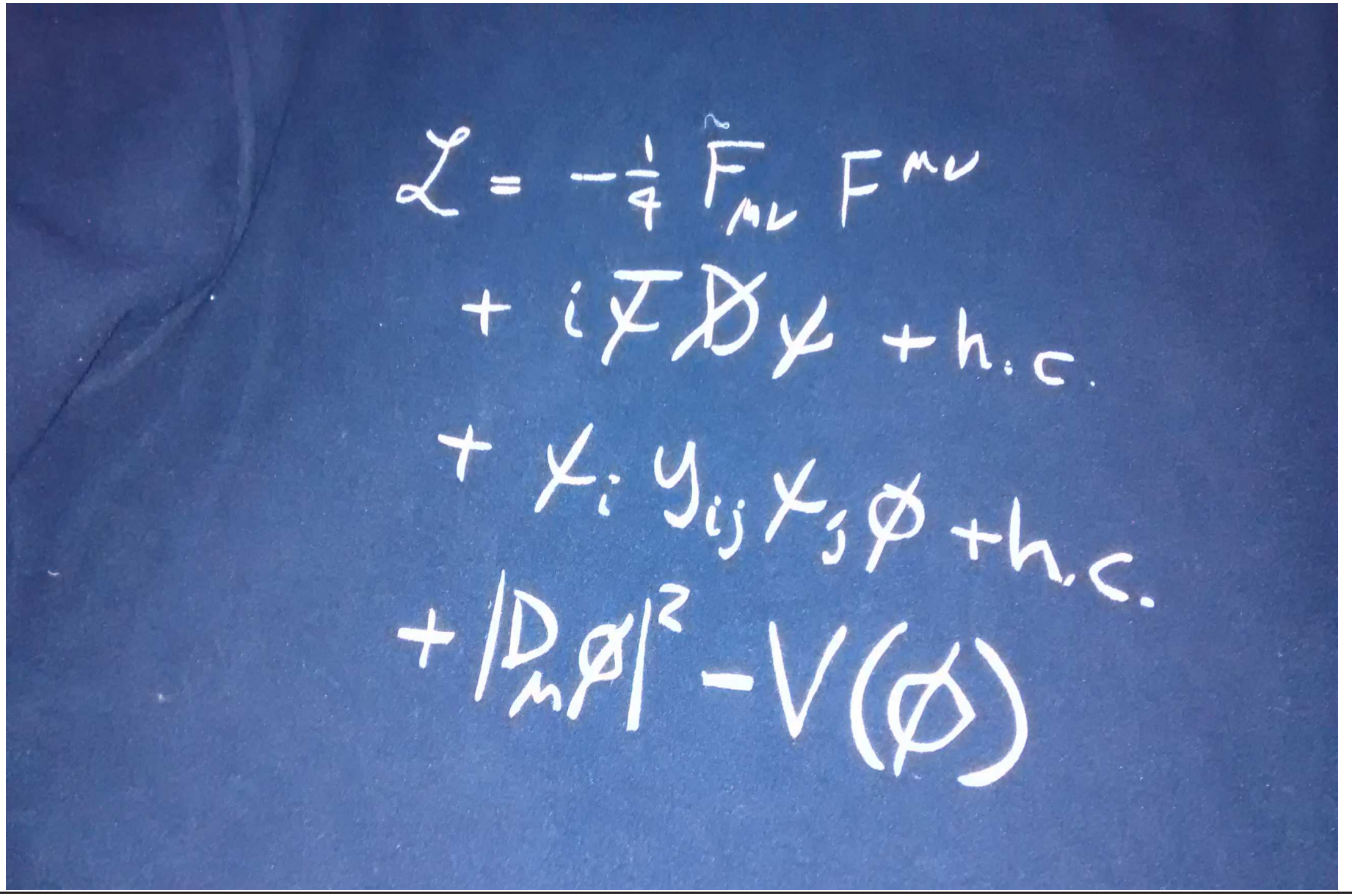


Standard Model (theory)

Rohini M. Godbole
Centre for High Energy Physics, IISc, Bangalore, India


$\mathcal{L} = -\frac{1}{4}\tilde{F}_{\mu\nu}F^{\mu\nu}$
$+ i\bar{\chi}\not{D}\chi + h.c.$
$+ \chi_i y_{ij} \chi_j \phi + h.c.$
$+ |D_\mu \phi|^2 - V(\phi)$

The Plan of the talk

- An *Ode* to the SM ☺

- SM *(mainly EW part)* as a Quantum Gauge Field Theory:

subtext: How consistency of EW theory itself pointed us to the missing parts and next goal posts!

- What is the new thing we learn about the SM **itself** from the Higgs discovery at the LHC!

- Future?

Statement number 1:

"In the present state of physical science, therefore, a question of extreme interest arises: Is there any principle on which **an absolute thermometric scale** can be founded?"

Statement number 2:

" There is nothing new to be discovered in physics now, All that remains is **more and more precise measurement**."

1. Existence of a EW scale **stable under radiative corrections** revealed. Is there a guiding principle on which the stability can be founded? We 'thought' we knew!..may be our thinking is right but...may be not!

2. All that remains is **more and more precise measurement** of the Higgs and top properties!

SM: $SU(3)_C \times SU(2)_L \times U(1)_Y$ Gauge Field Theory describing Strong and Electro Weak (Electromagnetic and Weak) Interactions.

Thus SM stands on the joint pillars of relativistically invariant quantum field theories and gauge symmetries.

The gauge invariance guarantees renormalisability.

The spontaneous symmetry breaking of course allows us to have massive gauge bosons with spontaneous breaking of the $SU(2)_L \times U(1)_Y$ Gauge symmetry.

Its success, culminating in the discovery of the Higgs Boson.

May be we are at a cusp and some people are asking the question whether it is time for a paradigm shift!

Before discussing and thinking about these things better to take stock of things as they are!

How we came to be here?

The 'Periodic Table' of Fundamental particles and their interactions has arrived!

FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin =1/2

Flavor	Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0–0.13)\times10^{-9}$	0
e electron	0.000511	–1
ν_M middle neutrino*	$(0.009–0.13)\times10^{-9}$	0
μ muon	0.106	–1
ν_H heaviest neutrino*	$(0.04–0.14)\times10^{-9}$	0
τ tau	1.777	–1

Quarks spin =1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.002	2/3
d down	0.005	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	173	2/3
b bottom	4.2	–1/3

BOSONS

force carriers
spin = 0, 1, 2, ...

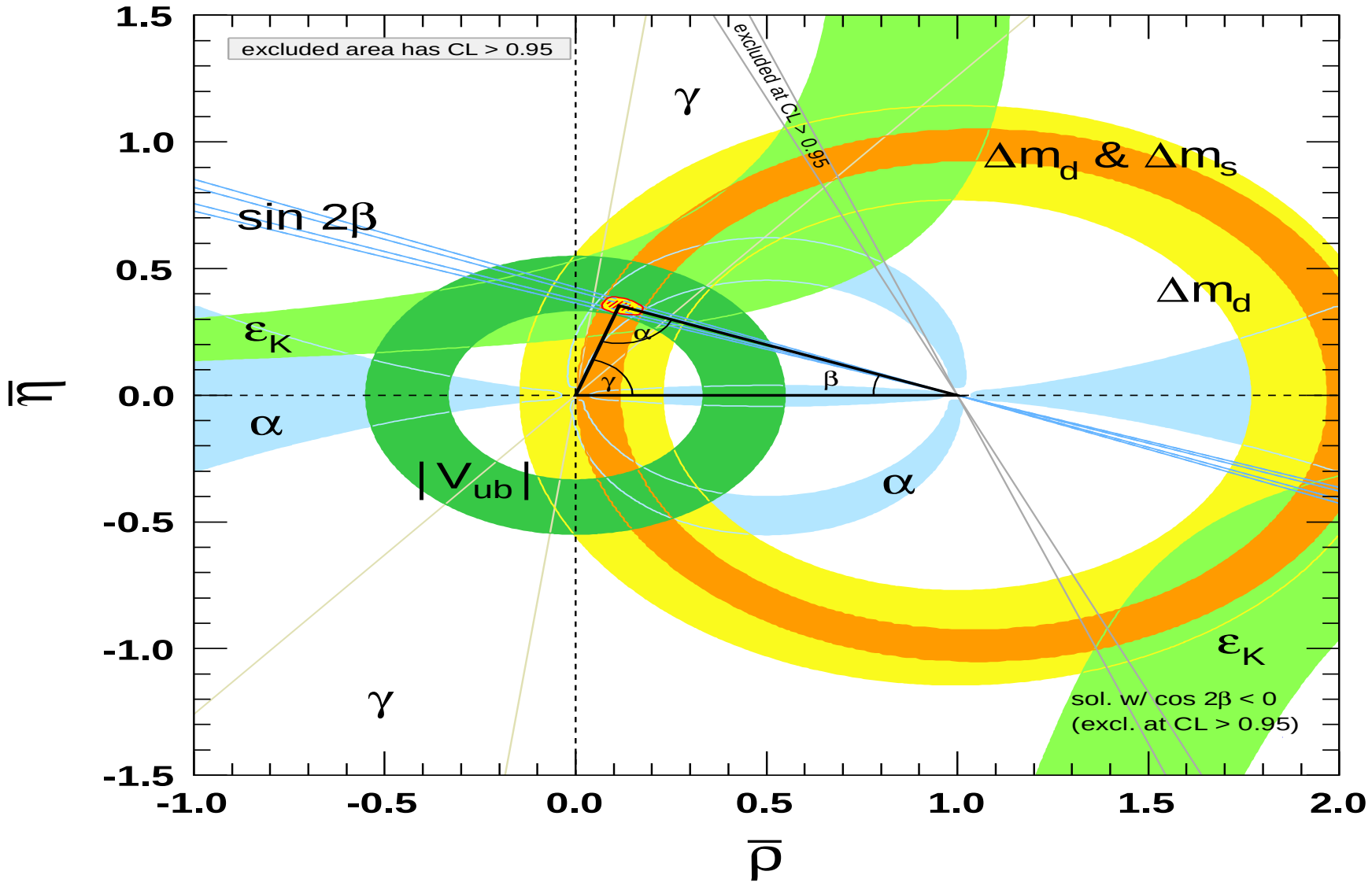
Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.39	–1
W^+ W bosons	80.39	+1
Z^0 Z boson	91.188	0

Strong (color) spin =1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

The force carriers are fundamental particles too!


excluded area has CL > 0.95
excluded at CL > 0.95
γ
Δm_d & Δm_s
sin 2β
Δm_d
ε_K
α
β
γ
|V_ub|
α
ε_K
γ
sol. w/ cos 2β < 0
(excl. at CL > 0.95)
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
η̄
ρ̄

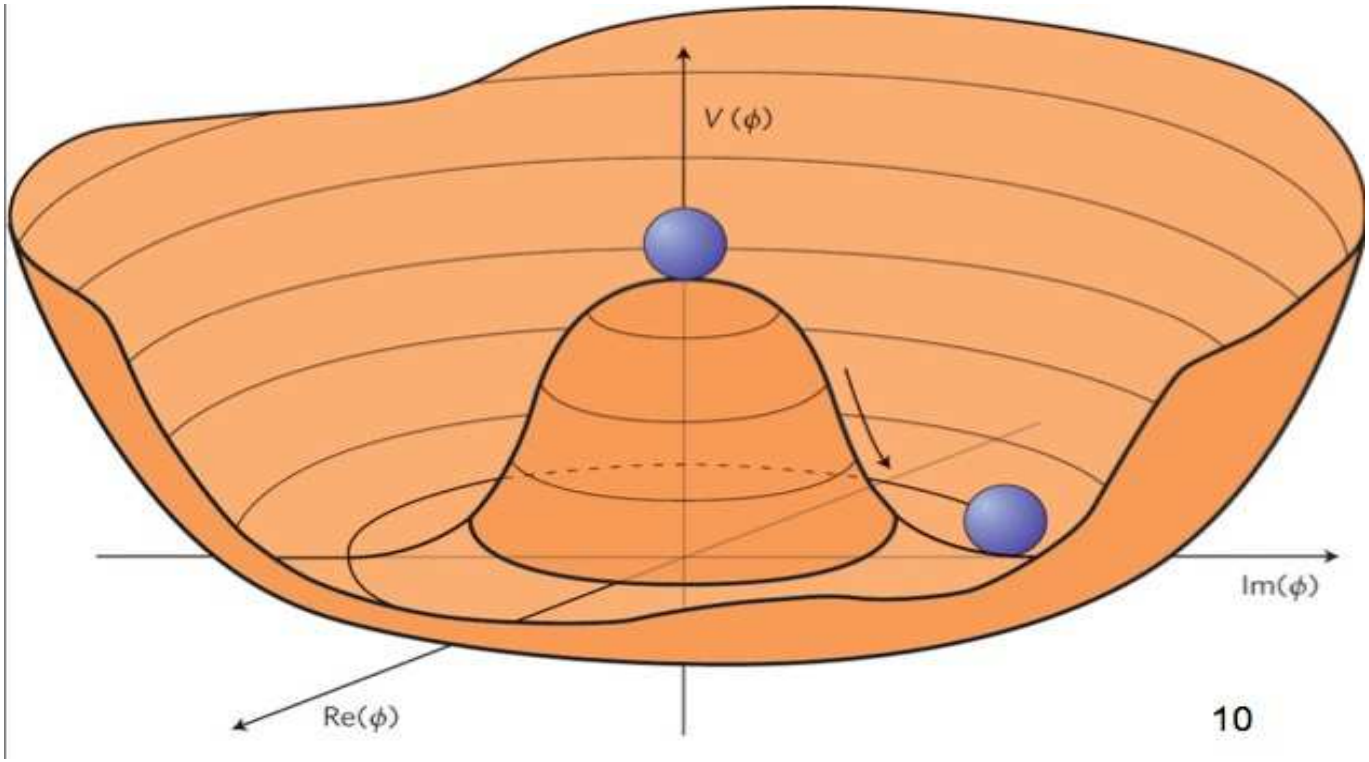
Generalities:

The SM Lagrangian consists of Gauge sector and the Scalar sector:

$$\mathcal{L} = -\frac{1}{4}F^a_{\mu\nu}F^{a\,\mu\nu} + i\bar{\psi}\not{D}\psi + f^*_e(\bar{\nu},\bar{e})_L\Phi e_R + f^*_u(\bar{u},\bar{d})_L\Phi^C u_R$$
$$+ ..... + h.c. + |D_\mu\Phi|^2 - \mu^2\Phi^\dagger\Phi - \lambda(\Phi^\dagger\Phi)^2$$

Gauge sector in very good shape Given that the Strong interaction part as well as idea of Spontaneous Symmetry breaking got the Nobels before July 4, 2012. Developments needed (and thus predicted) some part of fermion sector!

But the gauge theory needs the Scalar sector for it to be consistent!


V(ϕ)
Im(ϕ)
Re(ϕ)
10

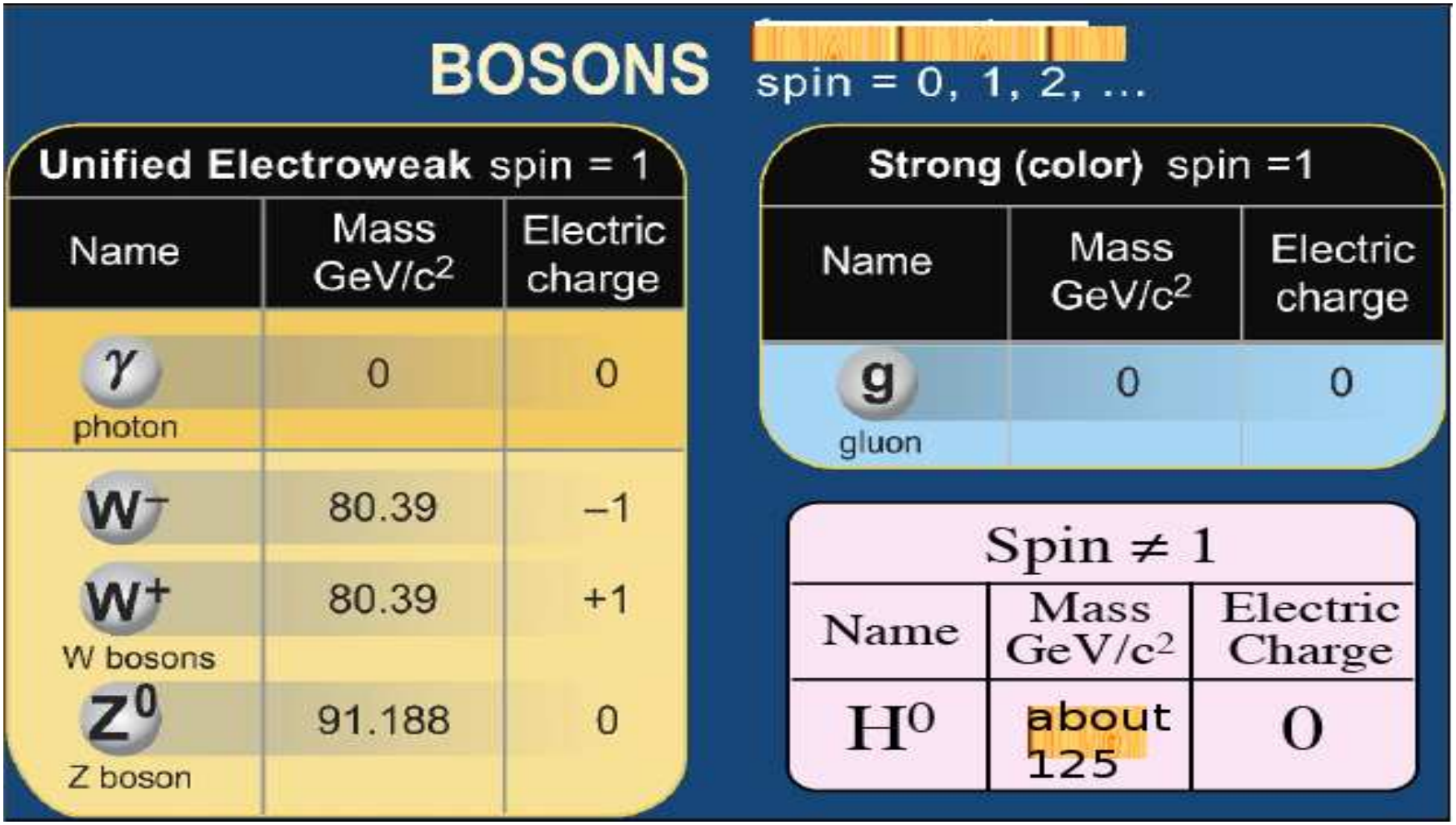
h is J = 0, CP even, Hypercharge Y= 1 and $SU(2)_L$ doublet.

Tree level $\bar{f}fh$, hVV , $hhVV$ couplings $\propto$ mass:

$$\lambda_f = \frac{m_f}{v}; \quad g_V = 2\frac{M_V^2}{v}; \quad g_{hhVV} = 2\frac{M_V^2}{v^2}.$$

Couplings to gg and $\gamma\gamma$ are loop induced!

July 4, 2012


BOSONS
spin = 0, 1, 2, ...
Unified Electroweak spin = 1
Name
Mass GeV/c²
Electric charge
γ
photon
0
0
W⁻
80.39
−1
W⁺
80.39
+1
W bosons
Z⁰
91.188
0
Z boson
Strong (color) spin =1
Name
Mass GeV/c²
Electric charge
g
gluon
0
0
Spin ≠ 1
Name
Mass GeV/c²
Electric Charge
H⁰
about 125
0

H^0 (Higgs Boson)

The observed signal is called a Higgs Boson in the following, although its detailed properties and in particular the role that the new particle plays in the context of electroweak symmetry breaking need to be further clarified. The signal was discovered in searches for a Standard Model (SM)-like Higgs. See the following section for mass limits obtained from those searches.

H^0 MASS

VALUE (GeV)	DOCUMENT ID	TECN	COMMENT
125.9±0.4 OUR AVERAGE			
125.8±0.4±0.4	[1] CHATRCHYAN 13J	CMS	pp, 7 and 8 TeV
126.0±0.4±0.4	[2] AAD 12AI	ATLS	pp, 7 and 8 TeV
• • • We do not use the following data for averages, fits, limits, etc. • • •			
126.2±0.6±0.2	[3] CHATRCHYAN 13J	CMS	pp, 7 and 8 TeV
125.3±0.4±0.5	[4] CHATRCHYAN 12N	CMS	pp, 7 and 8 TeV

HTTP://PDG.LBL.GOV Page 1 Created: 7/31/2013 15:05

2013 Update of the PDG!

We found it where we expected it. (More about it later)

Laws of particle physics which we have found to be functioning at distance scales of fermi's and smaller, seem to be of relevance in addressing things that happen on cosmological time (the early universe) and astronomical distance scales (cosmic phenomena!)

Calculation of relative abundance of elements requires knowledge of Nuclear reactions we measure in the laboratory!

Matter-antimatter asymmetry has at least an in principle understanding in terms of the SM.

As a theorist this is the ultimate success of a theory. It can explain things which you did not design it to explain!

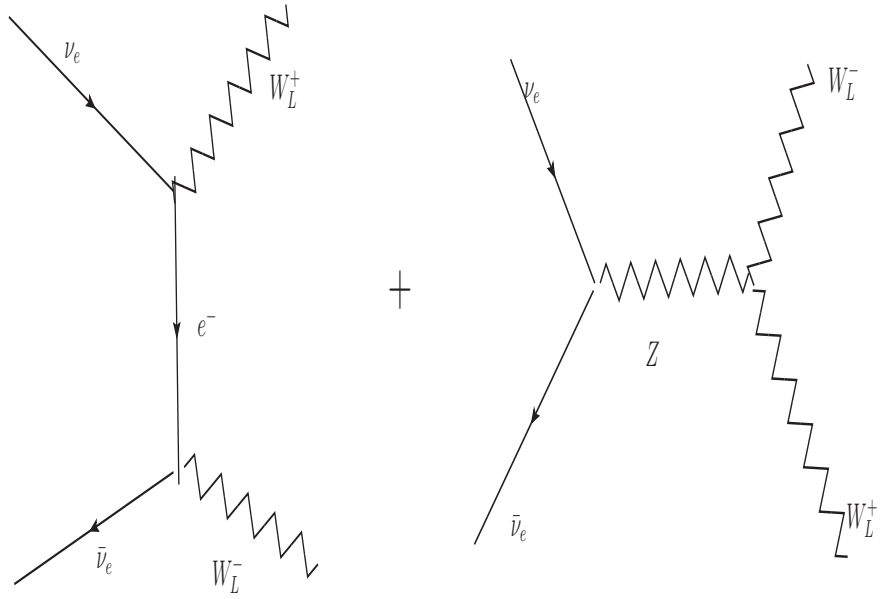
Note a very interesting point. Right from the beginning the EW theory itself told us where it is going to go wrong and correcting that wrong led us to the right theory.

If we recall right from the beginning it was the bad high energy behaviour (in principle) that forced us to extend our descriptions of weak interactions.

1. Fermi theory (Current-Current Interactions): $\mathcal{M}(\nu e \to \nu e)$ violates tree level unitarity for $\sqrt{s} \simeq 250 \sim G_F^{-1/2}$ GeV $\Rightarrow$ massive gauge bosons. Mass? Somewhere below this!

2. Even with a mass for the IVB, $\mathcal{M}(\nu_e \bar{\nu}_e \to W^+W^-$ grows fast with energy and violates unitarity.

3. S channel exchange of a Z boson in gauge theory with precisely the non abelian gauge couplings of $SU(2)_L \times U(1)$ gauge group restores the unitary behaviour. Divergence for $WW \to WW$ MUCH worse, also cured!.



J.S. Bell: Nuclear Physics, **B60**, 427, 1973:

Showed that in a renomalisable theory tree level amplitudes satisfy unitarity.

But three sets of authors asked the opposite question: What can we deduce by demanding that tree level amplitudes satisfy unitarity.

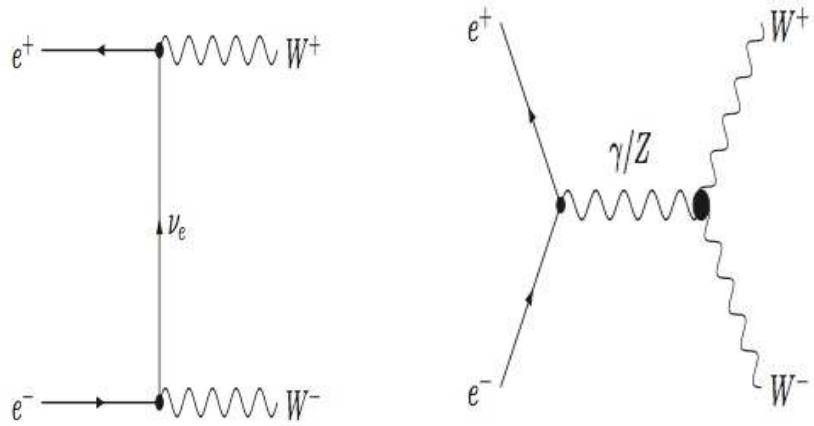
J. M. Cornwall, D. N. Levin and G. Tiktopoulos, PRL **30**, 1268 (1973), Phys.Rev. **D10**, 1145 (1974),

C. Llewllyn Smith : PLB **46**, 233 (1973)

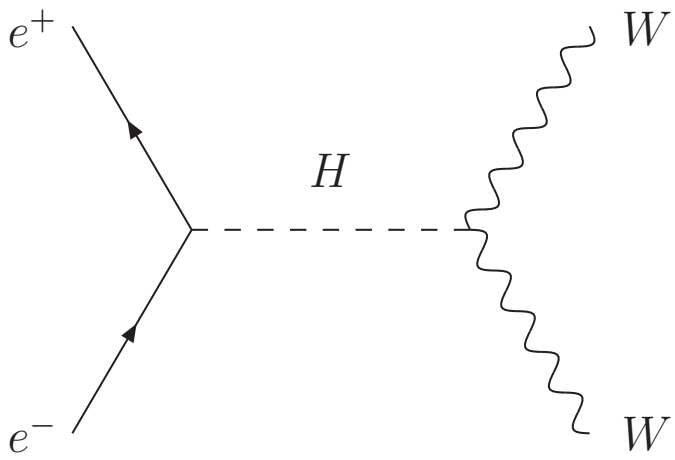
S.D. Joglekar,: Ann. Phys. **83**, 427 (1974)

They showed that such demands uniquely indicate spontaneously broken gauge theories.

For example:
Unitarity of $\mathcal{A}(e^+e^- \to W_L W_L)$, for example, $\Rightarrow$ Divergences cancel only if there is a $J = 0$ amplitude (s channel exchange of a Spin 0 particle) whose coupling to matter/gauge particles is proportional to their masses $\Rightarrow$ **Existence of a Higgs boson.**



But no knowledge on the scale! ie. the mass of the Higgs!
Only the couplings.



SSB Gauge theory makes scattering amplitudes well behaved at high energy, even with massive gauge bosons!.

In fact Higgs couplings to matter and gauge bosons required to be proportional to masses to have unitarity.

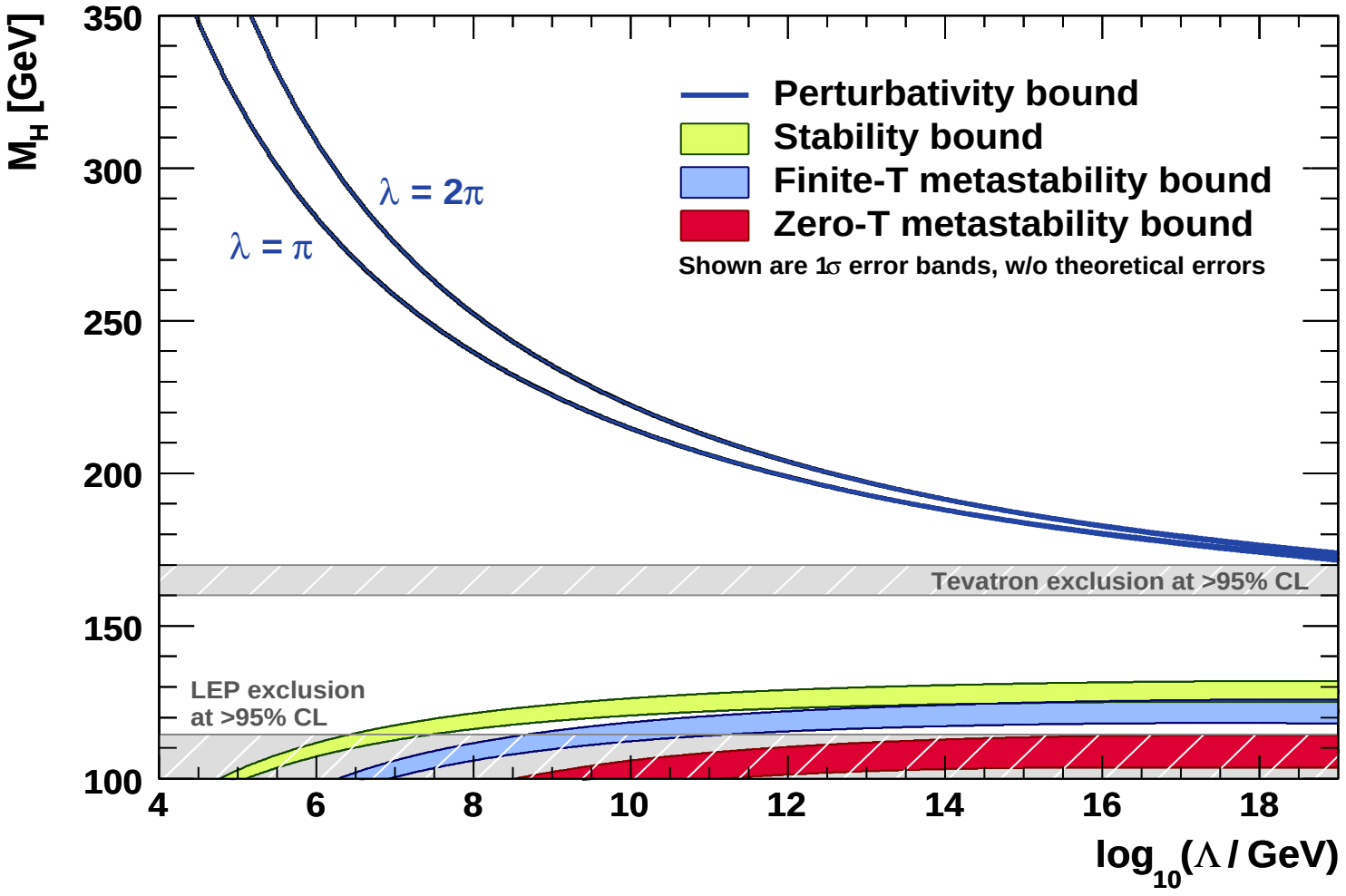
This is indeed one of the prediction of the renormalisable $SU(2)_L \times U(1)_Y$ where the EW symmetry broken spontaneously by the Higgs mechanism!

What about the Higgs mass?

Demanding a consistent quantum field theory (triviality and vacuum stability arguments) as well as the unitarity arguments give upper and lower BOUND!

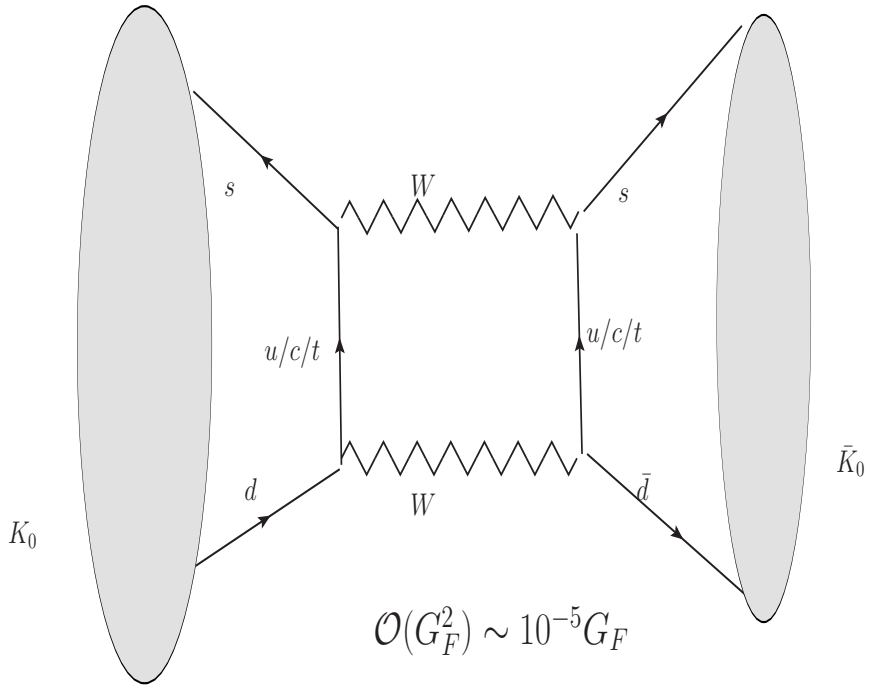
But just limits!

Subtext: m_h and fate of SM



We all agonized What if m_h was above the upper limit! Ultra violet completion of theories!

So the reported value around 125/126 GeV is very very special from this point of view. Will discuss a bit later.



Loop yields a finite result only in the four quark picture the result of the calculation and is

$$\frac{\Delta M_K}{M_K} = \frac{G_F^2}{4\pi} m_c^2 \cos^2\theta_c \sin^2\theta_c f_K^2$$

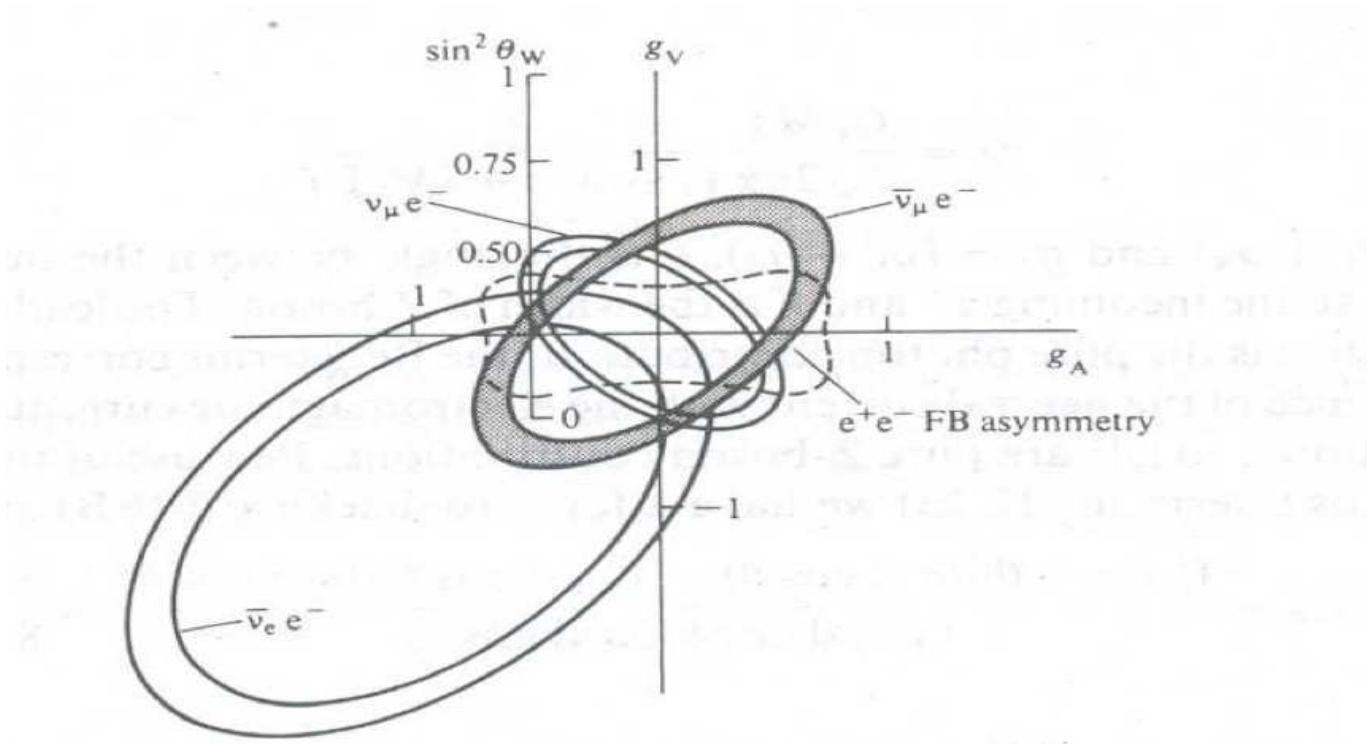
$$= 7 \times 10^{-15}$$

Predicts $m_c \sim 1.6$ GeV.

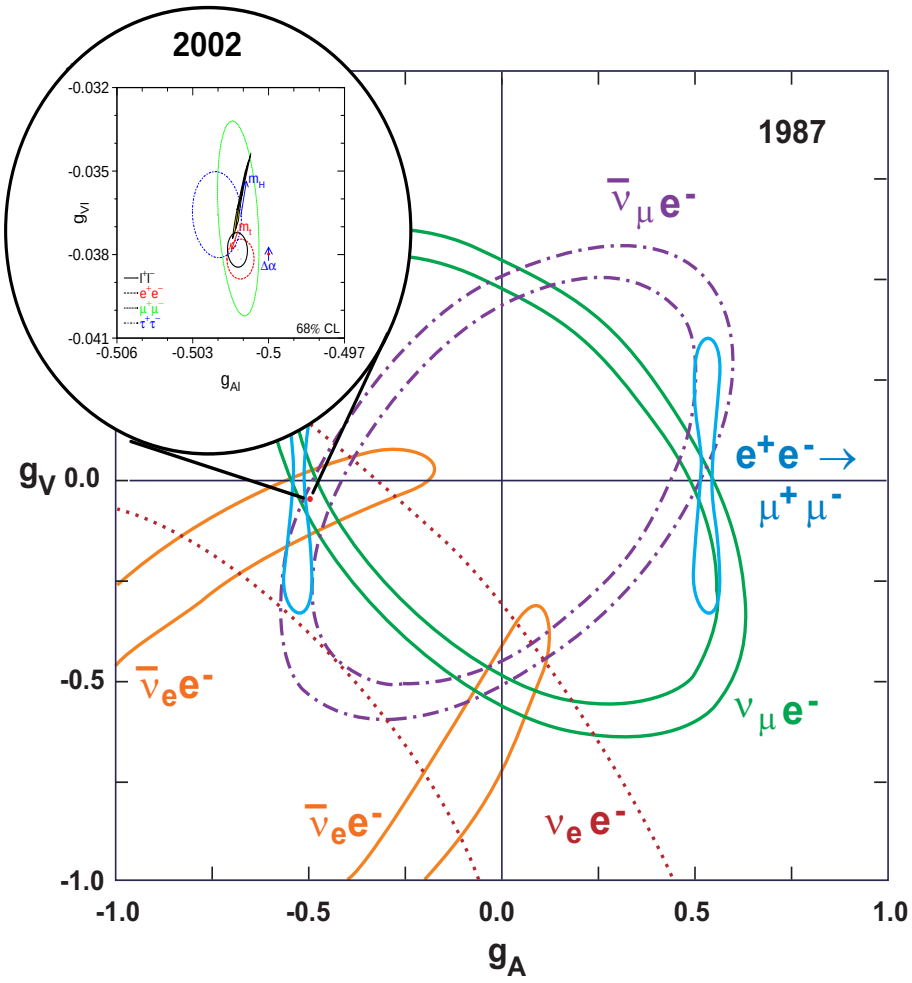
The November revolution: Discovery of Charmonium at 3.1 GeV was the first step in validation of the SM as a renormalisable Gauge theory!

NEEDS GIM!

Determination of Neutral Current couplings and hence $\sin^2\theta_W$ (circa 1981)



Predicted $M_W = 82 \pm 2, M_Z = 92 \pm 2$ GeV. Test of unified Gauge theory but not a Quantum Gauge Theory!

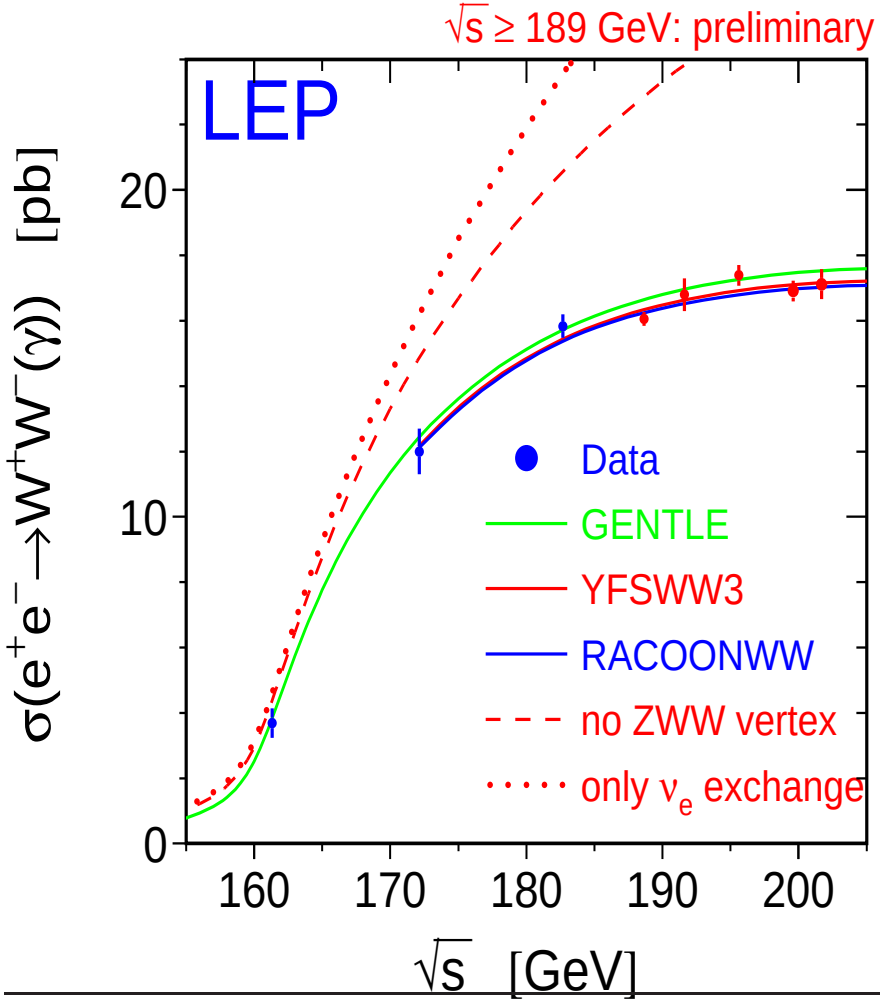


Without inclusion of loop effects now the SM would have been ruled out!

$M_W = 80.404 \pm 0.030$ GeV (measured), $80.376 GeV (theory)$

$m_t = 172.5 \pm 2.3$ GeV (measured)
172.9 GeV (theory)

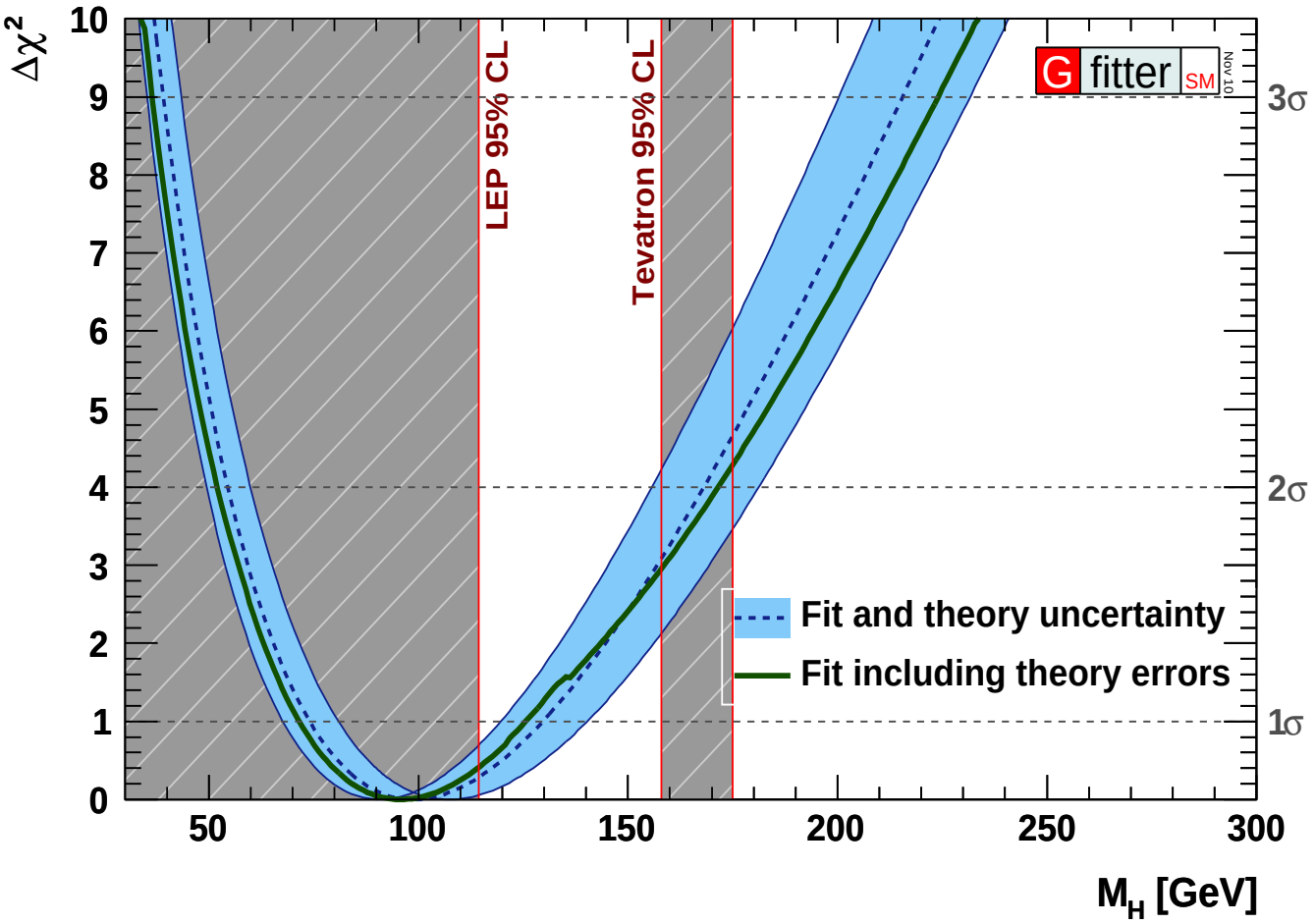
Direct 'Proof' of Symmetry and Symmetry breaking!!



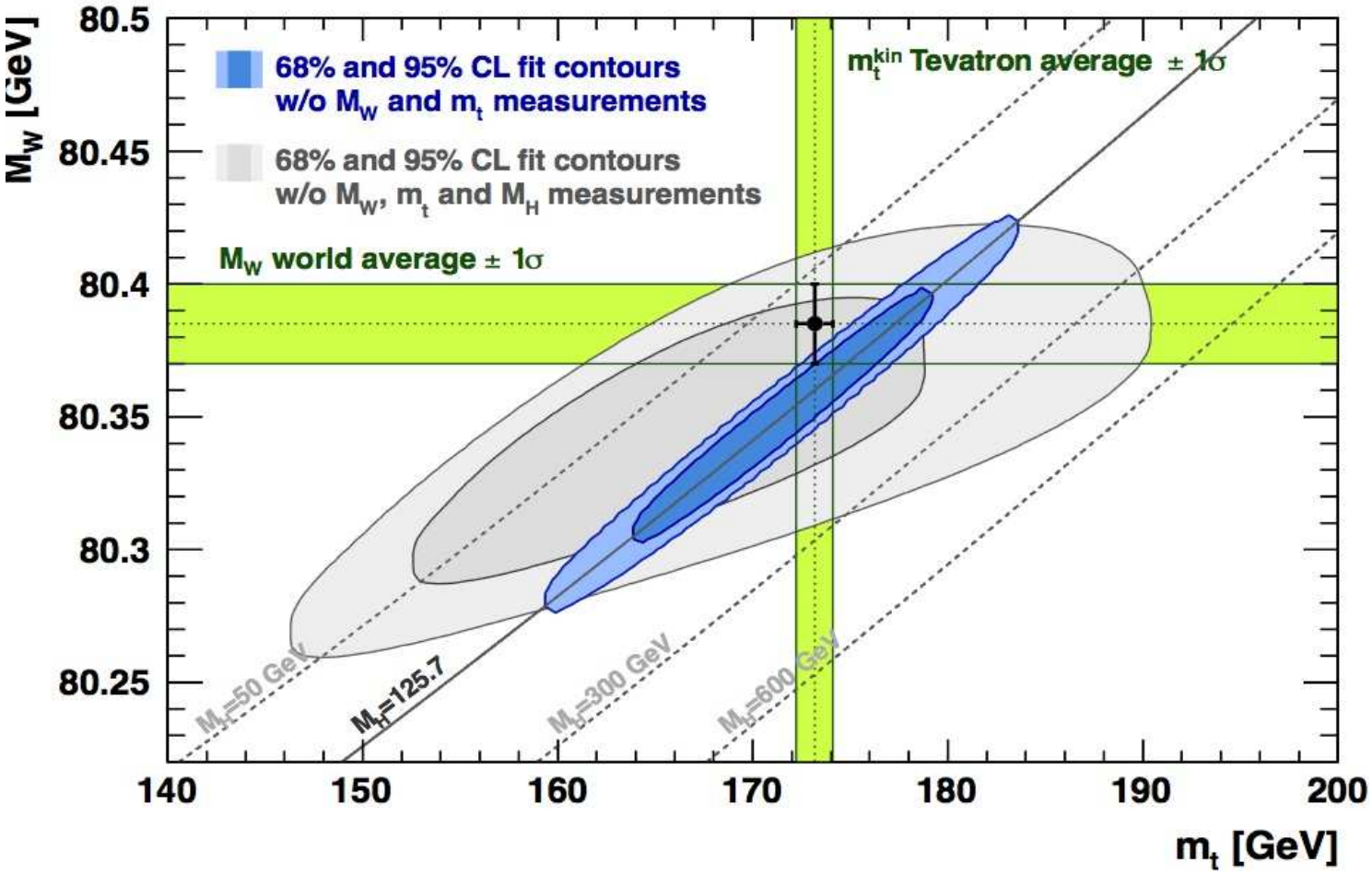
Proof that electroweak symmetry exists and that it is broken.

The triple gauge boson ZWW coupling tames the bad high energy behaviour of the cross-section caused by the t-channel diagram. Direct proof for the ZWW coupling.

This and precision testing, confirm basics of the SM



Higgs mass in the SM should be less than 160 GeV (Indirect information!) We knew this before the LHC was turned on!



SM rocks! **LOOP Level!**

This still does not tell us whether the SM is all that there is?

I.e is the SM a self-consistent theory all the way to Planck scale

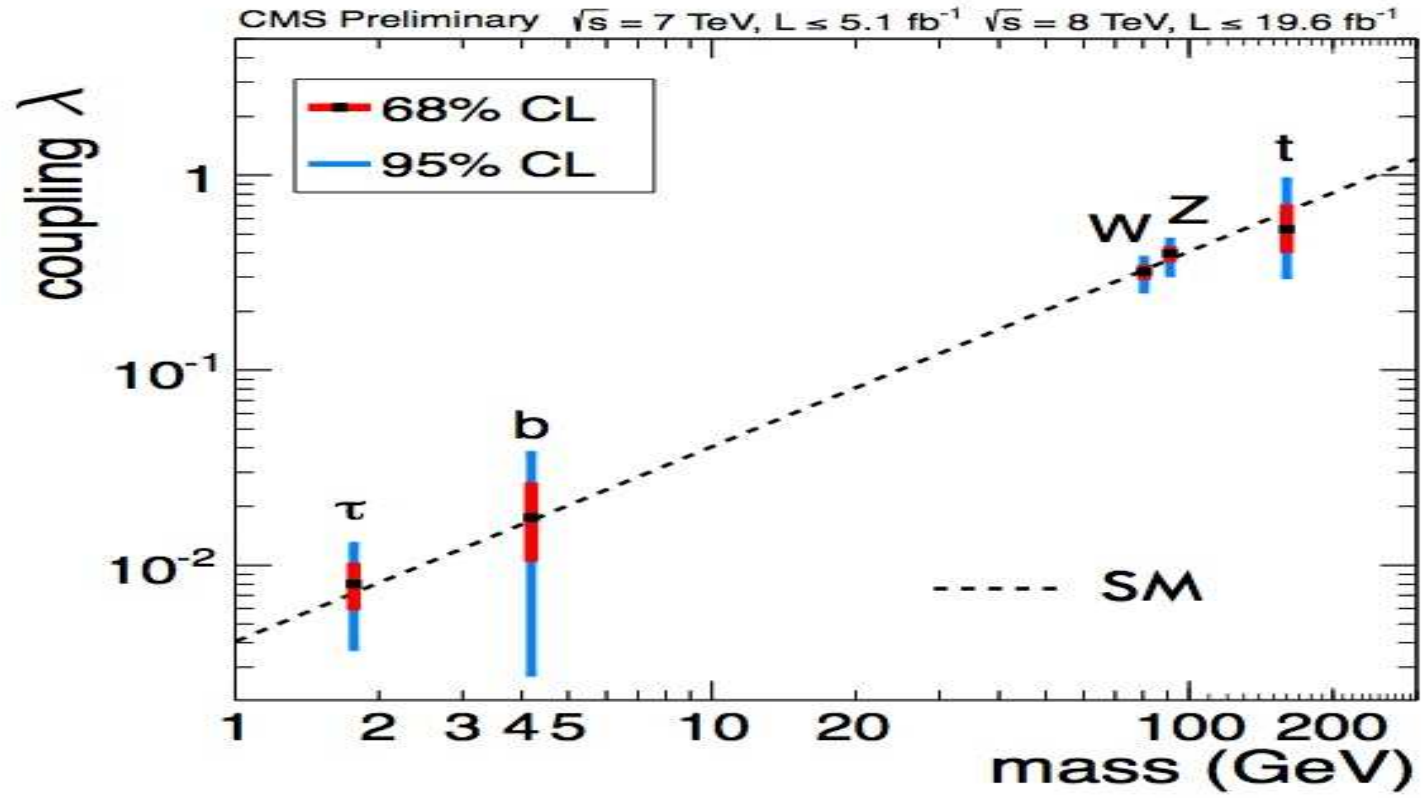
OR

Does it need something more?

The observed mass of the Higgs MAY be able to tell us something about it!

LHC results:

Direct information Mass, spin , parity and couplings.



For the first time 'direct' information on *some* of the fermion higgs coupling.

Note that $ht\bar{t}$ coupling information still indirect!

The mass of the observed state very very interesting from a lot of points of view!

Small enough to keep us still thinking of a mechanism like SUSY to stabilize it

and

Large enough to make us wonder whether SM is the ONLY thing all the way to the Planck Scale! (strengthened by absence of any BSM signal!)

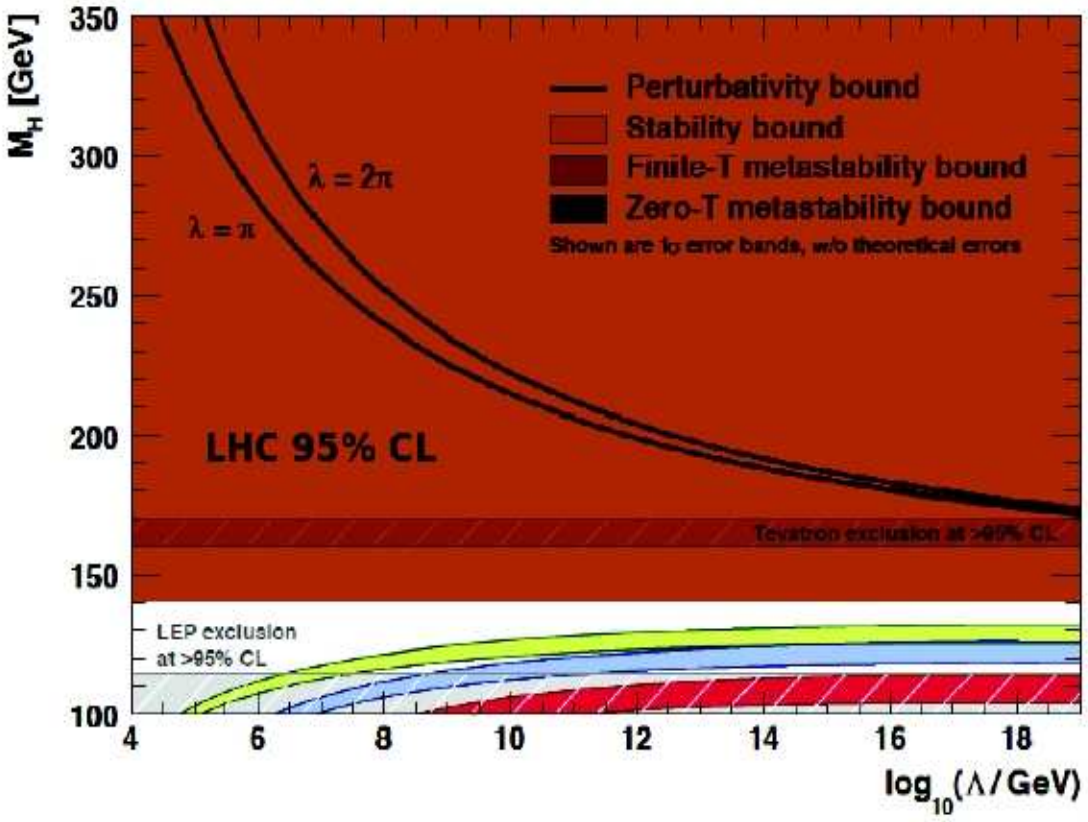
and

A unique value where decays into almost all final states are substantial

We want precision in measurements and **ALSO** in theory predictions!

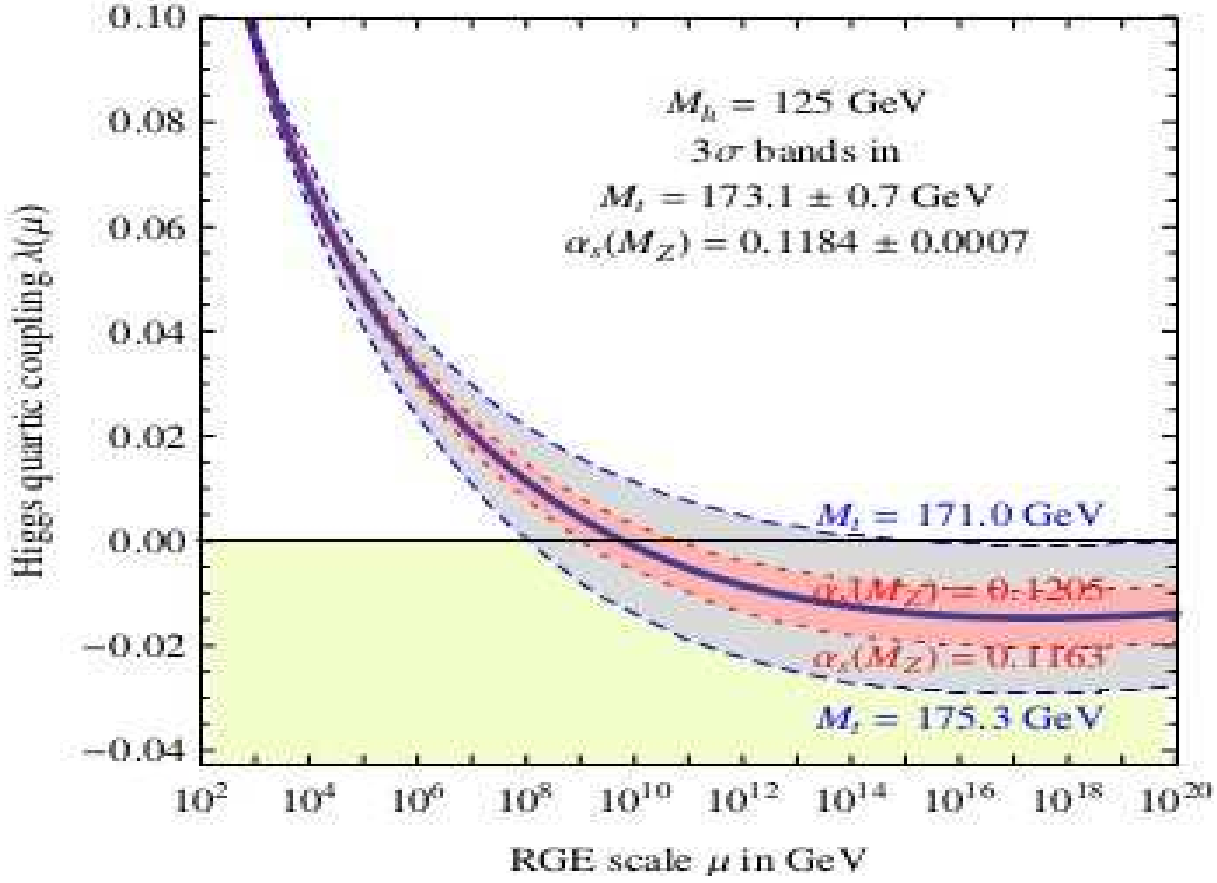
If there are anomalies hiding in tall 'elephant grass' we need to have pinpointed search lights! A very tough ask to decide whether the deviations are statistically significant!

Recall the theory limits on m_h!



Already in December 2011 it was clear that we need an accurate knowledge of the Lower limit. (slide courtsy: M. Kraemer)

De Grassie et al (1205.6497) Complete NNLO analysis. Major progress. Theoretical error on the obtained bounds due to missing higher order corrections reduced to 1 GeV



De Grassie analysis:

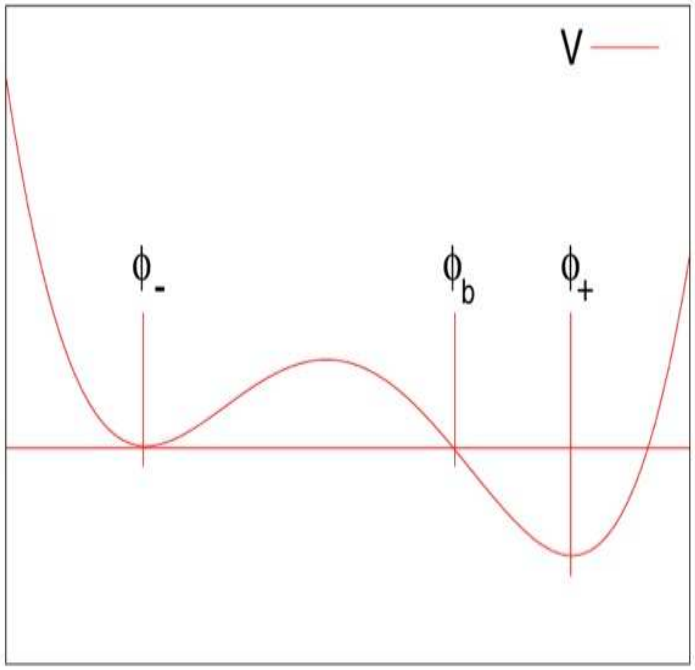
$$M_h \text{ [GeV]} > 129.4 + 1.4 \left(\frac{M_t \text{ [GeV]} - 173.1}{0.7} \right) - 0.5 \left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007} \right) \pm 1.0_{\text{th}}$$

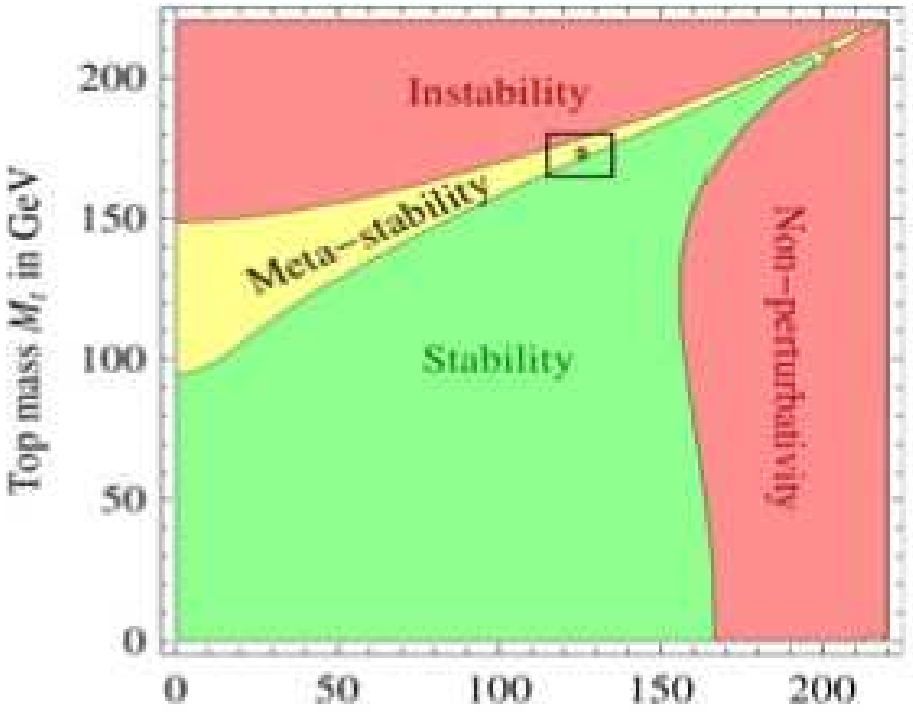
Use errors on pole mass $\Delta m_t = \pm 0.7$ GeV

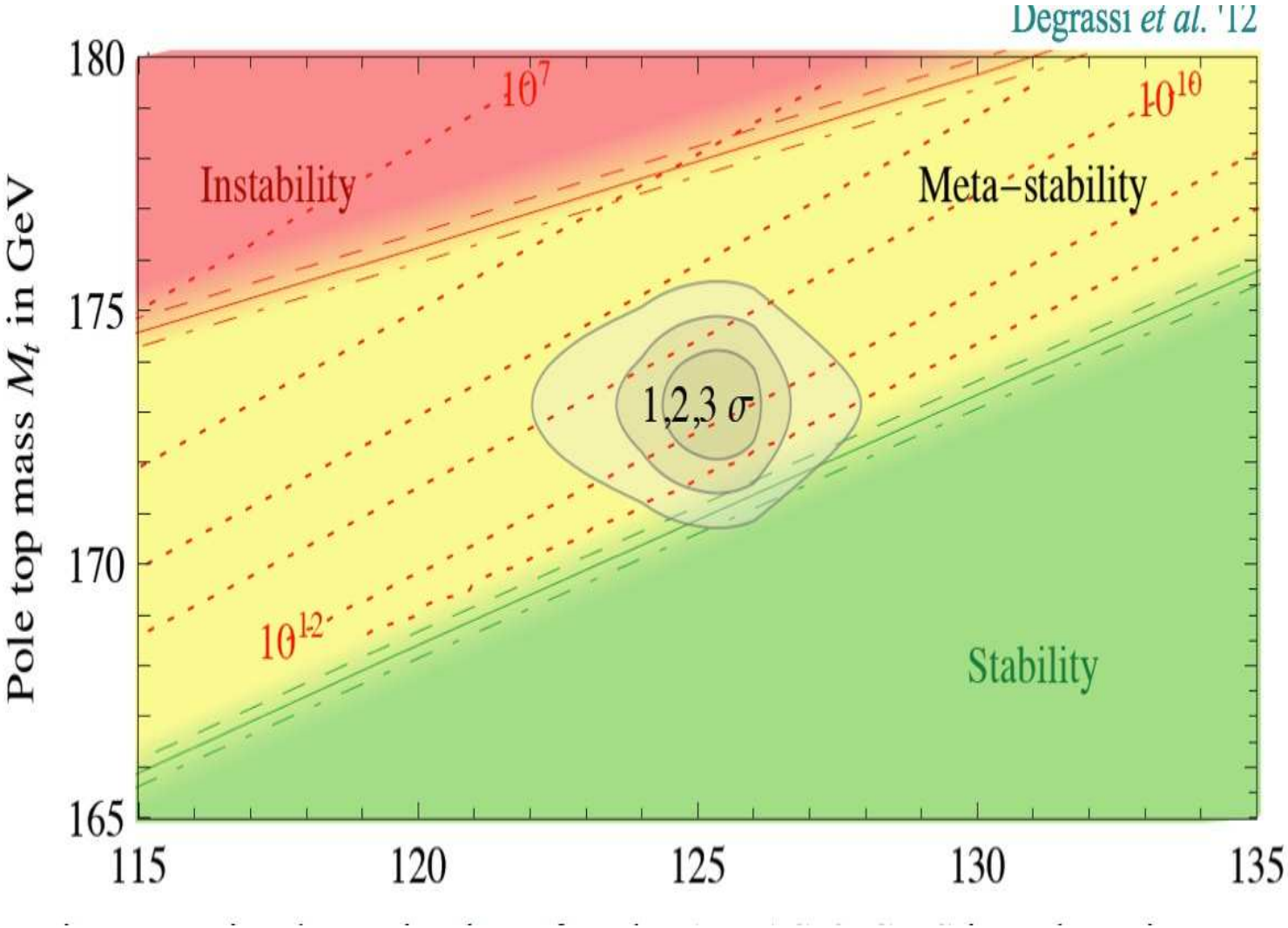
So for $m_h < 126$ GeV absolute vacuum stability of the SM all the way to Planck Scale is excluded at 98% c.l.

Planck scale dynamics might stabilise the vacuum for $|\Phi| >> v$ and we might be living in a metastable vacuum which has a life time bigger than that of the Universe.

How to calculate transition rates: Coleman showed us in 1977!






Degrassi et al. '12
Instability
Meta−stability
Stability
1,2,3 σ
10^{7}
10^{10}
10^{12}
Pole top mass M_t in GeV
180
175
170
165
115
120
125
130
135

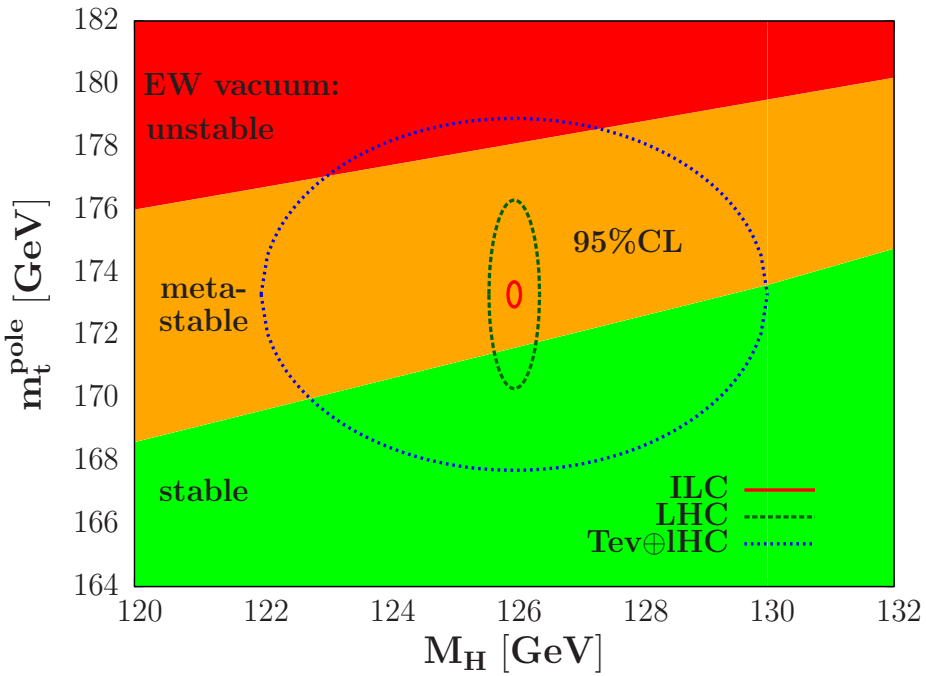
Reconsider the stability bounds given by Giudice et al. They used errors on m_t as measured at the Tevatron/LHC : the so called kinematic mass.

Moch et al : extract the $\bar{M}S$ mass of the top quark from the measurement of the top quark cross-sections at the Tevatron and the NNLO calculation. Led to larger errors!

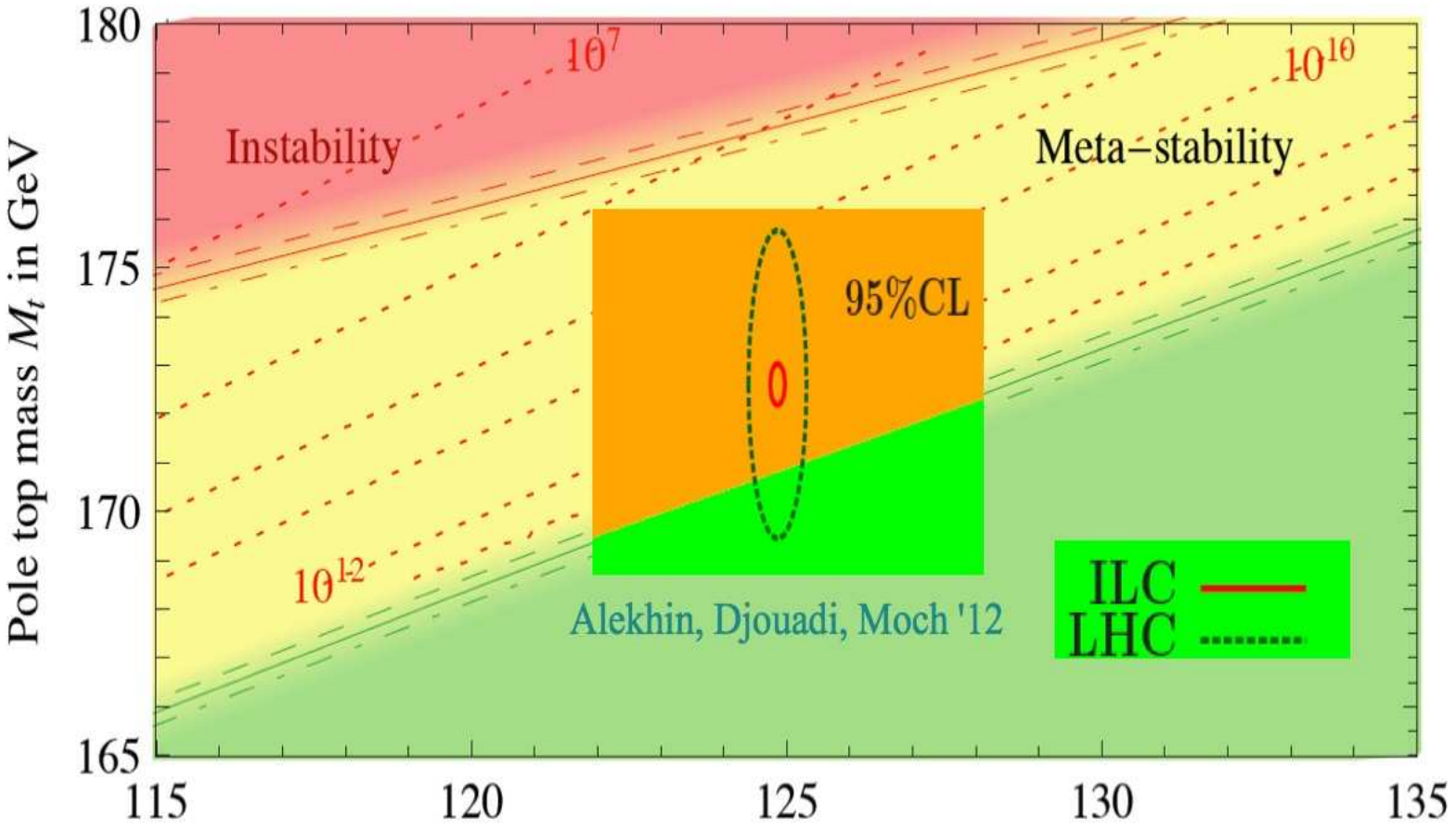
Estimate: $m_t^{pole} = 173.3 \pm 2.8$ GeV.

Vacuum stability constraint now becomes $m_h > 129.4 \pm 5.6$ GeV.

So the conclusion about the scale up to which SM is valid without getting into conflict with vacuum stability is weakened.

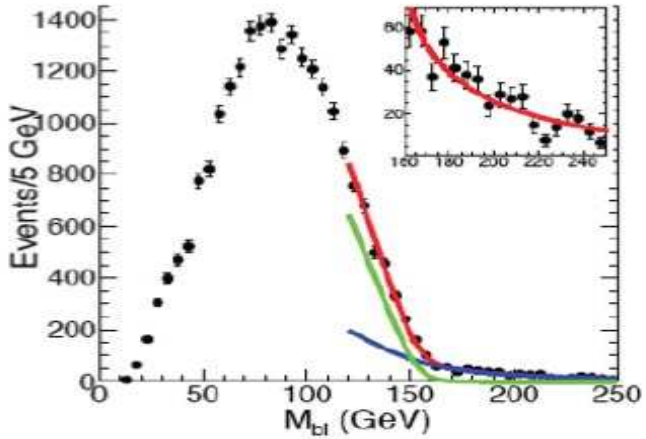


So the precision measurement of the mass at the ILC can really shed light whether higgs mass point to the **NEED** of BSM physics at a **particular scale**.


Pole top mass M_t in GeV
180
175
170
165
115
120
125
130
135
Instability
Meta−stability
10^{7}
10^{10}
10^{12}
95%CL
0
Alekhin, Djouadi, Moch '12
ILC
LHC

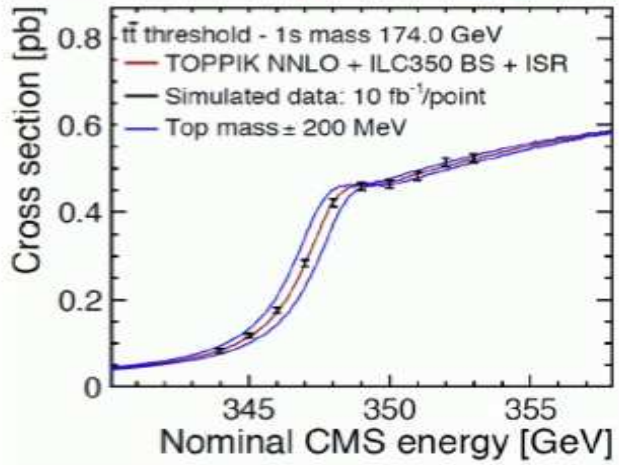
Top Quark Mass

LHC



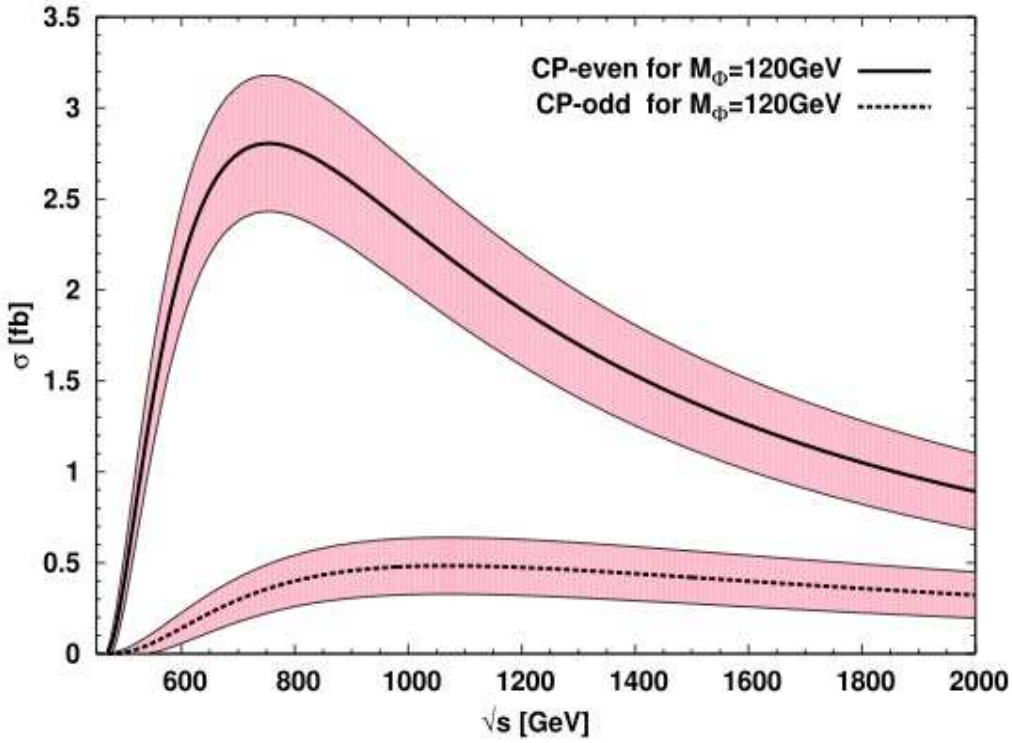
Kinematic reconstruction
Fit to invariant mass distr.
"MC" mass close to "pole" mass?

ILC [ILC TDR 2013]



Threshold scan ⇒ threshold mass
Transition to other mass
definitions possible

Can measure also $t\bar{t}h$ coupling directly including the CP structure unambiguously! $e^+e^- \to t\bar{t}H$ has a different threshold rise for scalar and pseudoscalar: ZPC 71, 1681 (R.G. M. Muhellleitner, etal) Can even measure/bound CP mixing in Higgs without ambiguity!



Peeping through the Higgs window!

LHC:

Seems to have found the light Higgs

BUT

So far no evidence for the different BSM particles.

The mass and the couplings of this light state might be the window through which we can get a view of BSM at present!

'Anticipating' the scale of BSM physics is a bit like anticipating the Higgs mass in the SM. We had no prediction for it, but then there were precision constraints.

Can we probe BSM like this? Indeed one can, through the mass of the Higgs, the Higgs coupling, implications for vacuum stability!

In any case the days of Standard Model are coming to an end in some sense!

Hopefully the case will be 'The King is Dead', 'Long live the King'!

Already the mass of the observed state can be used to answer the question about the scale unto which the SM is valid.

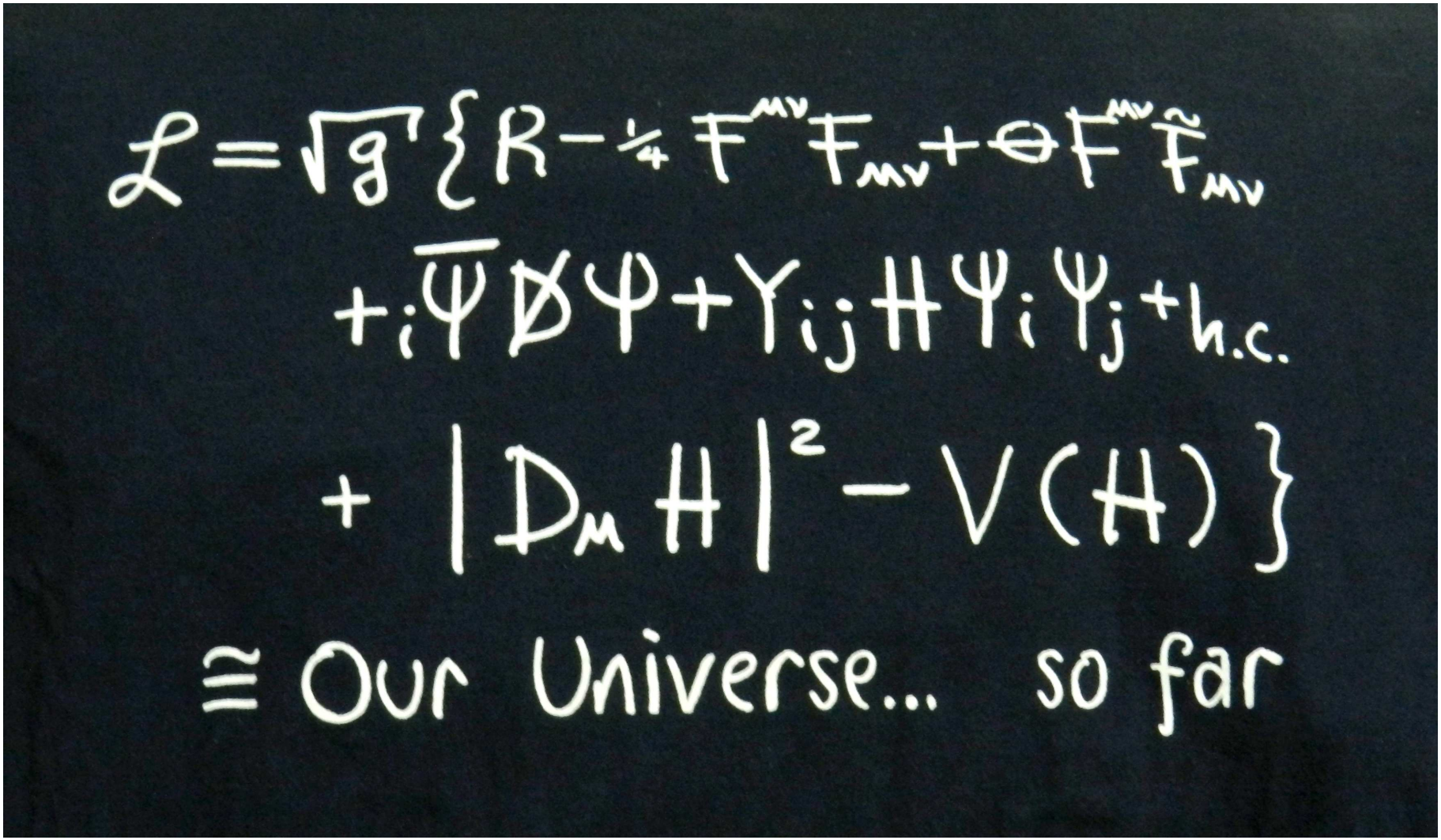
Just like the **gauge principle** and the **unitarity** were the guiding principle so far now the **'light' scalar** might be the guiding principle for future developments!

We should get a peek at the BSM land through the 'window' of measurement of the properties of the Higgs!

Exciting days ahead for sure!

If 14 TeV LHC should also fail to find 'direct' evidence for the BSM physics we would really have to understand what is so special about the Standard Model and hopefully that answer won't be Anthropic Principle !


BSM
HIGGS


$\mathcal{L} = \sqrt{g}\{R - \frac{1}{4} F^{\mu\nu} F_{\mu\nu} + \Theta F^{\mu\nu} \tilde{F}_{\mu\nu}$
$+ i\bar{\Psi} \not{D} \Psi + Y_{ij} H \Psi_i \Psi_j + h.c.$
$+ |D_\mu H|^2 - V(H)\}$
$\cong$ Our Universe... so far