The Standard Model
Precision tests and issues

Lecture 4

A.V. Bednyakov

(No MUG, sorry)

Parameters of the SM (minimal version)

$$(g_s, g \equiv g_2, g' \equiv g_1), (\lambda, m^2), (Y_u, Y_d, Y_l, V_{\text{CKM}})$$

$$\mathcal{L}_{\text{gauge}} \qquad \mathcal{L}_{\text{higgs}} \qquad \mathcal{L}_{\text{Yukawa}}$$

$$m_f = Y_f \frac{v}{\sqrt{2}} \qquad \alpha_s = \frac{g_s}{4\pi}$$

$$\alpha = \frac{e^2}{4\pi}, \quad e = gg'/\sqrt{g^2 + g'^2} = g \sin\theta_W = g' \cos\theta_W$$

$$M_Z = \frac{\sqrt{g^2 + g'^2}v}{2}, \qquad M_W = \frac{gv}{2}$$

$$M_H^2 = 2\lambda v^2, \qquad v^2 = \frac{-m^2}{\lambda}, \ (m^2 < 0)$$

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~~Tevatron~~ LHC!

Not measured

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Parameters of the SM (minimal version)

- All observables can be predicted in terms of N_{par} = 18 (?) parameters

$$O_i(E) = O_i(E, \alpha, \alpha_s, M_Z, M_W, M_H, M_t, \ldots)$$

where E corresponds to some charesterstic energy scale.

- If we meausere at least N_{par} different observables we can extract the values of the parameters from the experiment and make predictions....

- Rather naive question:
  - Why can't we extract all the parameters just from ONE observable by choosing different E_i,i=1,N_{par}?

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  - Can't we extract all the parameters just from ONE observable by choosing different E_i,i=1,N_{par}?

In princple «YES»:
- Choose appropriate O_i
- Calculate RADIATIVE corrections as precise as possible (dependence on all the parameters)
- Get what you want!

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In practice «NO»!
sensitivity is different
for different parameters!

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OK, not all (just one, e.g., M_H) and not from a single observable....(See below).

Consistency check of the SM

- Given $N > N_{par}$ observables one can check the consistency of the model, since the latter predicts the relations between observables.

$$O_i(E) = O_i(E, \alpha, \alpha_s, M_Z, M_W, M_H, M_t, \dots)$$

- In practice: use as many observables as possible and do a fit
  - e.g. ZFITTER or GFITTER
    for ElectroWeak Precision Observables (EWPO)

Precision SM observables

- Low energy
  - Fermi G_μ constant measured in muon decay
  - Anomalous magnetic moment of muon $(g-2)_\mu$
- Z-pole observables
  - Z-boson mass and width M_Z, Γ_Z
  - Effective couplings of Z to fermions g_V, g_A
  - Effective Weinberg angle $\sin^2\theta_{\mathrm{lept}}$
- LEP 2, Tevatron, LHC:
  - W-boson mass M_W
  - Top quark mass M_t

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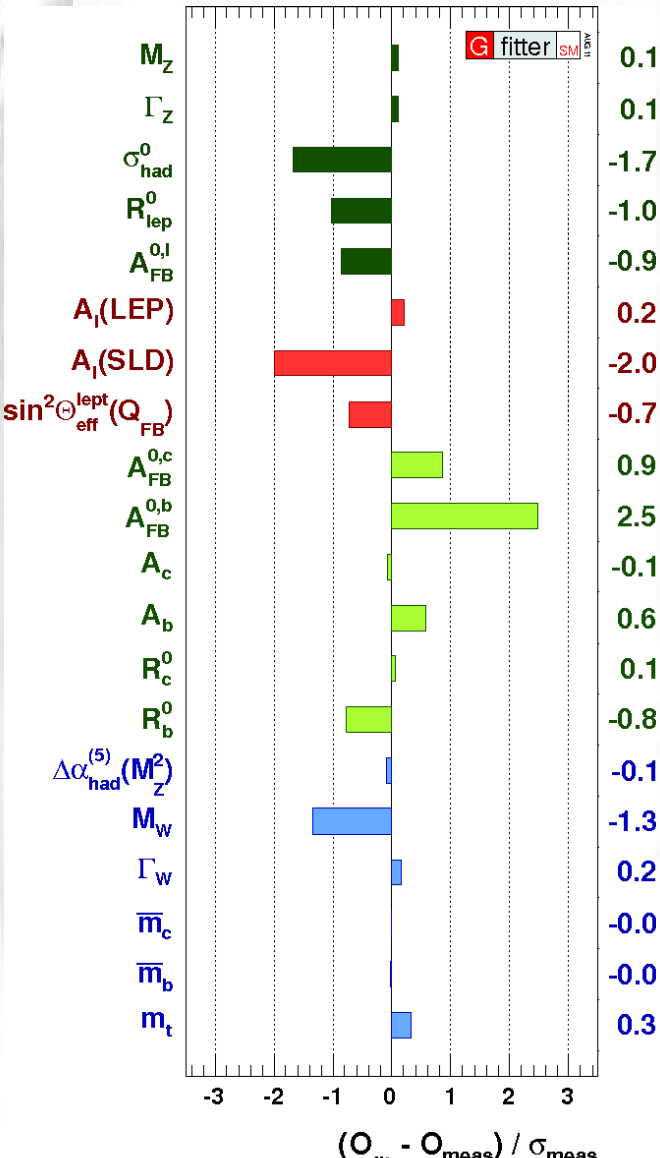
Gfitter fit :)



Parameter	Input value	Free in fit	Results from global EW fits: *Standard fit*	*Complete fit*	*Complete fit w/o exp. input in line*
M_Z [GeV]	91.1875 ± 0.0021	yes	91.1874 ± 0.0021	91.1877 ± 0.0021	$91.1983^{+0.0133}_{-0.0155}$
Γ_Z [GeV]	2.4952 ± 0.0023	–	2.4959 ± 0.0015	2.4955 ± 0.0014	$2.4951^{+0.0017}_{-0.0016}$
$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037	–	41.478 ± 0.014	41.478 ± 0.014	41.469 ± 0.015
R^0_ℓ	20.767 ± 0.025	–	20.743 ± 0.018	20.741 ± 0.018	$20.718^{+0.027}_{-0.026}$
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010	–	0.01641 ± 0.0002	$0.01620^{+0.0002}_{-0.0001}$	0.01606 ± 0.0001
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	–	0.1479 ± 0.0010	$0.1472^{+0.0009}_{-0.0006}$	–
A_c	0.670 ± 0.027	–	$0.6683^{+0.00044}_{-0.00043}$	$0.6680^{+0.00040}_{-0.00028}$	$0.6679^{+0.00042}_{-0.00025}$
A_b	0.923 ± 0.020	–	$0.93470^{+0.00009}_{-0.00008}$	$0.93463^{+0.00008}_{-0.00005}$	$0.93463^{+0.00007}_{-0.00005}$
$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035	–	0.0741 ± 0.0005	$0.0737^{+0.0005}_{-0.0004}$	0.0738 ± 0.0004
$A^{0,b}_{\rm FB}$	0.0992 ± 0.0016	–	0.1037 ± 0.0007	$0.1035^{+0.0003}_{-0.0004}$	$0.1038^{+0.0003}_{-0.0005}$
R^0_c	0.1721 ± 0.0030	–	0.17226 ± 0.00006	0.17226 ± 0.00006	0.17226 ± 0.00006
R^0_b	0.21629 ± 0.00066	–	$0.21578^{+0.00005}_{-0.00008}$	$0.21577^{+0.00005}_{-0.00008}$	$0.21577^{+0.00005}_{-0.00007}$
$\sin^2\theta^\ell_{\rm eff}(Q_{\rm FB})$	0.2324 ± 0.0012	–	0.23141 ± 0.00012	$0.23150^{+0.00008}_{-0.00011}$	$0.23152^{+0.00006}_{-0.00013}$
M_H [GeV] $^{(\circ)}$	Likelihood ratios	yes	$95^{+30[+74]}_{-24[-43]}$	$125^{+8[+21]}_{-10[-11]}$	$95^{+30[+74]}_{-24[-43]}$
M_W [GeV]	80.399 ± 0.023	–	$80.382^{+0.014}_{-0.015}$	$80.368^{+0.007}_{-0.010}$	$80.360^{+0.012}_{-0.011}$
Γ_W [GeV]	2.085 ± 0.042	–	2.093 ± 0.001	2.092 ± 0.001	$2.091^{+0.002}_{-0.001}$
$\overline{m}_c$ [GeV]	$1.27^{+0.07}_{-0.11}$	yes	$1.27^{+0.07}_{-0.11}$	$1.27^{+0.07}_{-0.11}$	–
$\overline{m}_b$ [GeV]	$4.20^{+0.17}_{-0.07}$	yes	$4.20^{+0.16}_{-0.07}$	$4.20^{+0.16}_{-0.07}$	–
m_t [GeV]	173.2 ± 0.9	yes	173.3 ± 0.9	173.5 ± 0.9	$177.2^{+2.9}_{-3.1}$ $^{(\triangledown)}$
$\Delta\alpha^{(5)}_{\rm had}(M^2_Z)$ $^{(\dagger\triangle)}$	2749 ± 10	yes	2750 ± 10	2748 ± 10	2716^{+60}_{-45}
$\alpha_s(M^2_Z)$	–	yes	0.1192 ± 0.0028	0.1193 ± 0.0028	0.1193 ± 0.0028
$\delta_{\rm th} M_W$ [MeV]	$[-4,4]_{\rm theo}$	yes	4	4	–
$\delta_{\rm th} \sin^2\theta^\ell_{\rm eff}$ $^{(\dagger)}$	$[-4.7,4.7]_{\rm theo}$	yes	4.7	4.7	–

$^{(\star)}$Average of LEP ($A_\ell = 0.1465 \pm 0.0033$) and SLD ($A_\ell = 0.1513 \pm 0.0021$) measurements. The fit w/o the LEP (SLD) measurement but with the direct Higgs searches gives $A_\ell = 0.1471^{+0.0010}_{-0.0008}$ ($A_\ell = 0.1467^{+0.0007}_{-0.0004}$). $^{(\circ)}$In brackets the 2σ. $^{(\dagger)}$In units of 10^{-5}. $^{(\triangle)}$Rescaled due to α_s dependency. $^{(\triangledown)}$Ignoring a second less significant minimum, *cf.* fig. ?? and the result of eq. (??).

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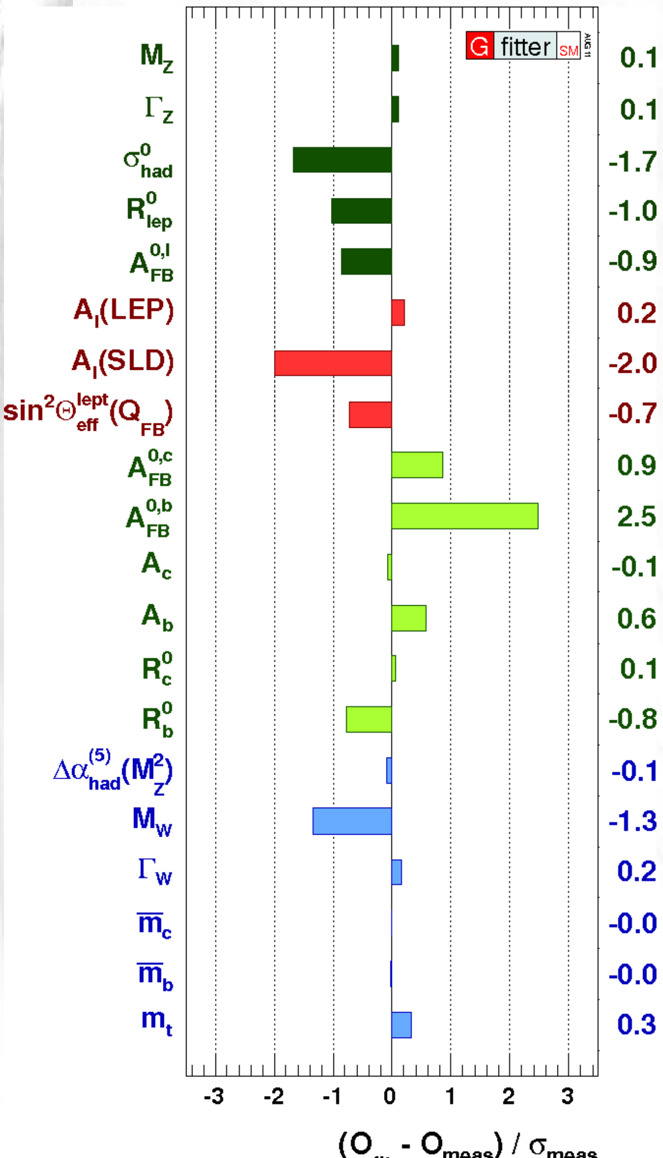

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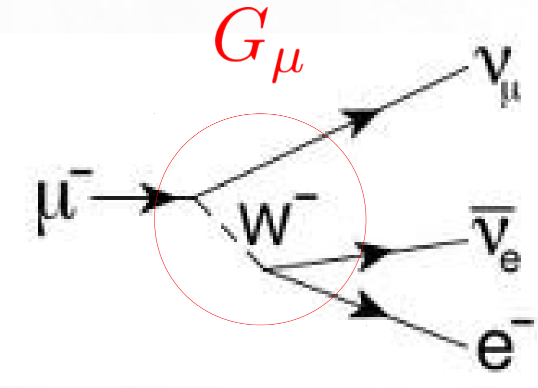
One-loop corrections included

Why do we need to go beyond tree-level?

$$G_F = 1.16637(1) \times 10^{-5}\ \mathrm{GeV}^{-5}$$

$$\frac{G_\mu}{\sqrt{2}} = \frac{g}{2\sqrt{2}} \frac{1}{M_W^2} \frac{g}{2\sqrt{2}}$$



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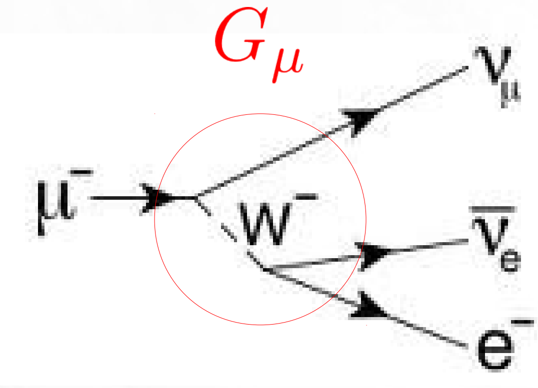
$$\frac{G_\mu}{\sqrt{2}} = \frac{g^2}{8M_W^2} = \frac{e^2}{8\sin^2\theta_W M_W^2}$$



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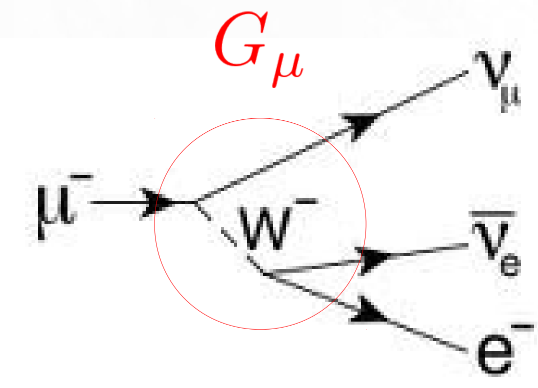


Tree-level

$$M_W^{\mathrm{tree}} = 80.9388(15)\mathrm{GeV}$$

$$M_W^{\mathrm{exp}} = 80.399(23)\mathrm{GeV}$$

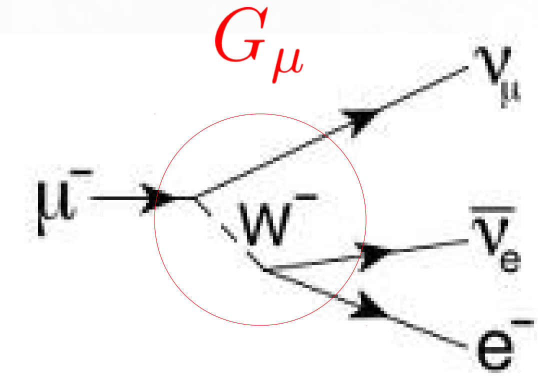
23σ difference

We need to include high order effects!

$$\alpha = 1/137.035999679, M_Z = 91.1876(28)\ \mathrm{GeV}$$

Why do we need to go beyond tree-level?

At high orders one needs to specify a renormalization scheme to define the renormalized parameters



We were considering

- physical masses M_Z, M_W
  $\rightarrow$ ON-SHELL renormalization prescription

- $\alpha(q^2 = 0)$ fine-structure constant in MOM-scheme

$$\frac{G_\mu}{\sqrt{2}} = \frac{\pi\alpha}{2M_W^2(1 - M_W^2/M_Z^2)}$$

SM

Fermi theory

Typical MATCHING problem

Comparison of observables
In «effective» and «fundamental» theories

Loop corrections

$$\rho = \frac{m_W^2}{m_Z^2 \cos^2\theta_W} = 1 \quad \Longrightarrow \quad \bar{\rho} = 1 + \Delta\rho$$

$$\sin^2\theta_W = 1 - \frac{m_W^2}{m_Z^2} \quad \Longrightarrow \quad \sin^2\theta_{eff} = (1 + \Delta\kappa)\sin^2\theta_W$$

$$m_W^2 = \frac{\pi\alpha}{\sqrt{2}\sin^2\theta_W G_F} \quad \Longrightarrow \quad m_W^2 = \frac{\pi\alpha}{\sqrt{2}\sin^2\theta_W G_F}(1 + \Delta r)$$

$$\alpha(0) \quad \Longrightarrow \quad \alpha(m_Z^2) = \frac{\alpha(0)}{1 - \Delta\alpha}$$

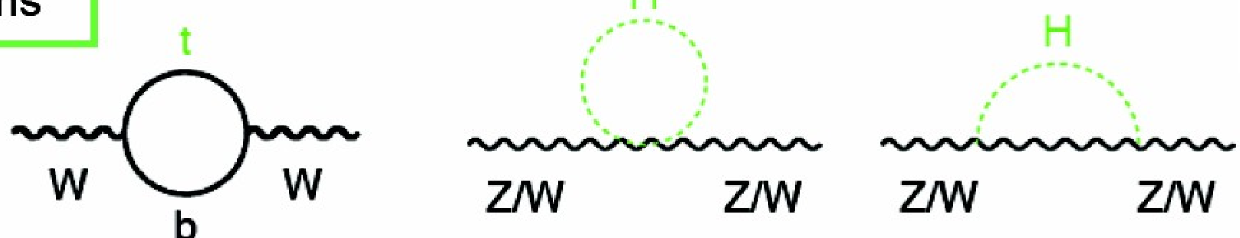
with : $\Delta\alpha = \Delta\alpha_{lept} + \Delta\alpha_{top} + \Delta\alpha_{had}^{(5)}$

Lowest order SM predictions

Including radiative corrections

$$\Delta\rho, \Delta\kappa, \Delta r = f\,(m_t^2, \log(m_H), \ldots)$$

Loop diagrams



Loop corrections

with loop contributions

$$\frac{G_F}{\sqrt{2}} = \frac{\pi\alpha}{M_W^2\left(1 - M_W^2/M_Z^2\right)} \cdot (1 + \Delta r)$$

Δr : quantum correction

$\Delta r = \Delta r(m_t, M_H)$

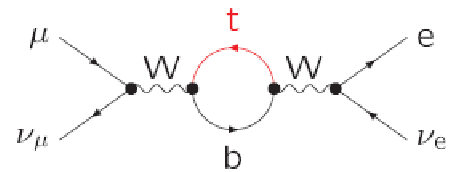
determines W mass

$$M_W = M_W(\alpha, G_F, M_Z, m_t, M_H)$$

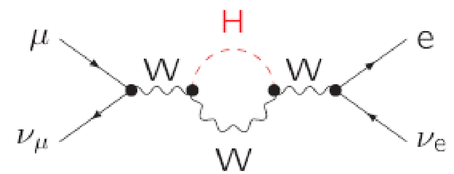
complete at 2-loop order

1-loop examples

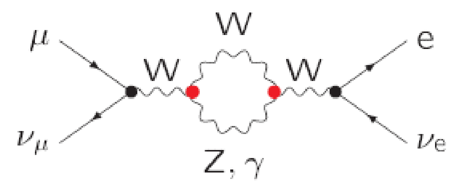
- top quark



- Higgs boson



- gauge-boson self-couplings



full structure of SM

Loop corrections

with loop contributions

$$\frac{G_F}{\sqrt{2}} = \frac{\pi\alpha}{M_W^2\left(1 - M_W^2/M_Z^2\right)} \cdot (1 + \Delta r)$$

Δr : quantum correction

$$\Delta r = \Delta r(m_t, M_H, m_Z, m_W, \ldots.)$$

determines W mass

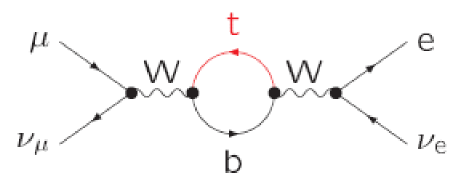
$$M_W = M_W(\alpha, G_F, M_Z, m_t, M_H)$$

complete at 2-loop order

Try to FIT it!

1-loop examples

- top quark



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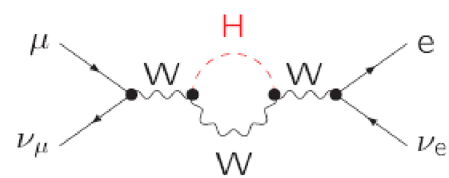

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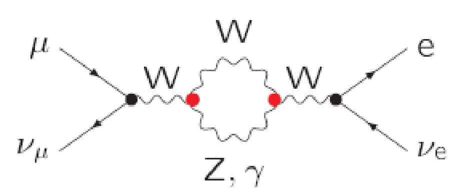

full structure of SM

Loop corrections

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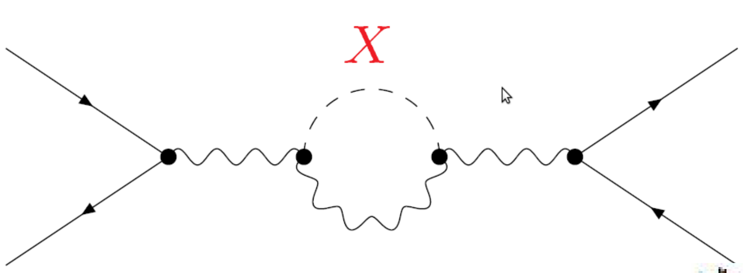
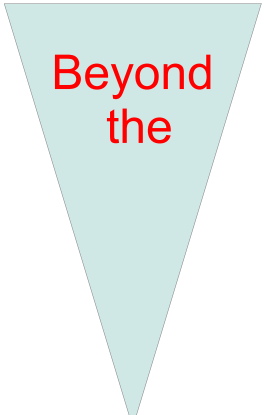
1-loop examples

$$\frac{G_F}{\sqrt{2}} = \frac{\pi\alpha}{M_W^2\,(1 - M_W^2/M_Z^2)} \cdot (1 + \Delta r)$$



Δr : quantum correction

$$\Delta r = \Delta r(m_t, M_H, m_Z, m_W, \mathbf{M}_\mathrm{X})$$

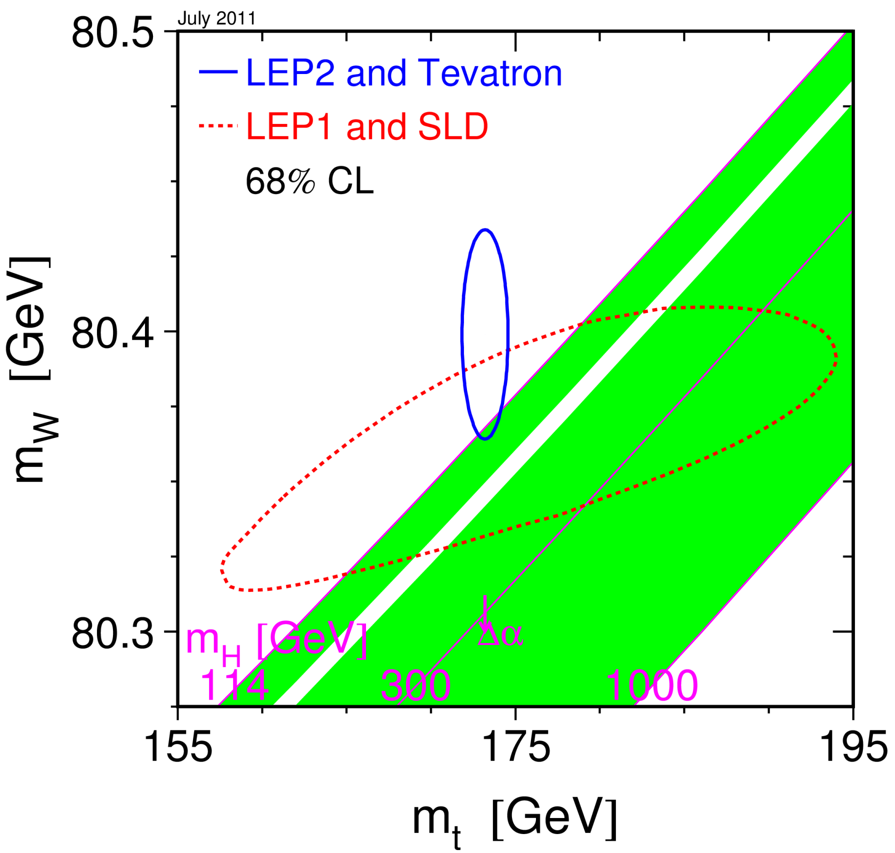


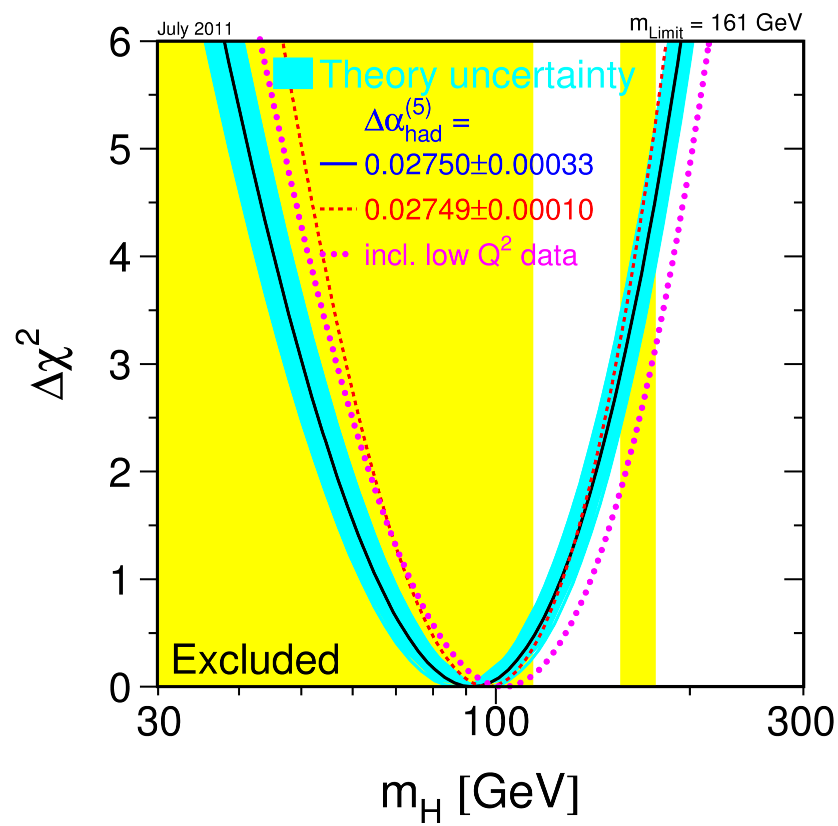
New Physics modify the relations!
Constraint it together with the Higgs

«EWPO constraints on NP»

full structure of SM

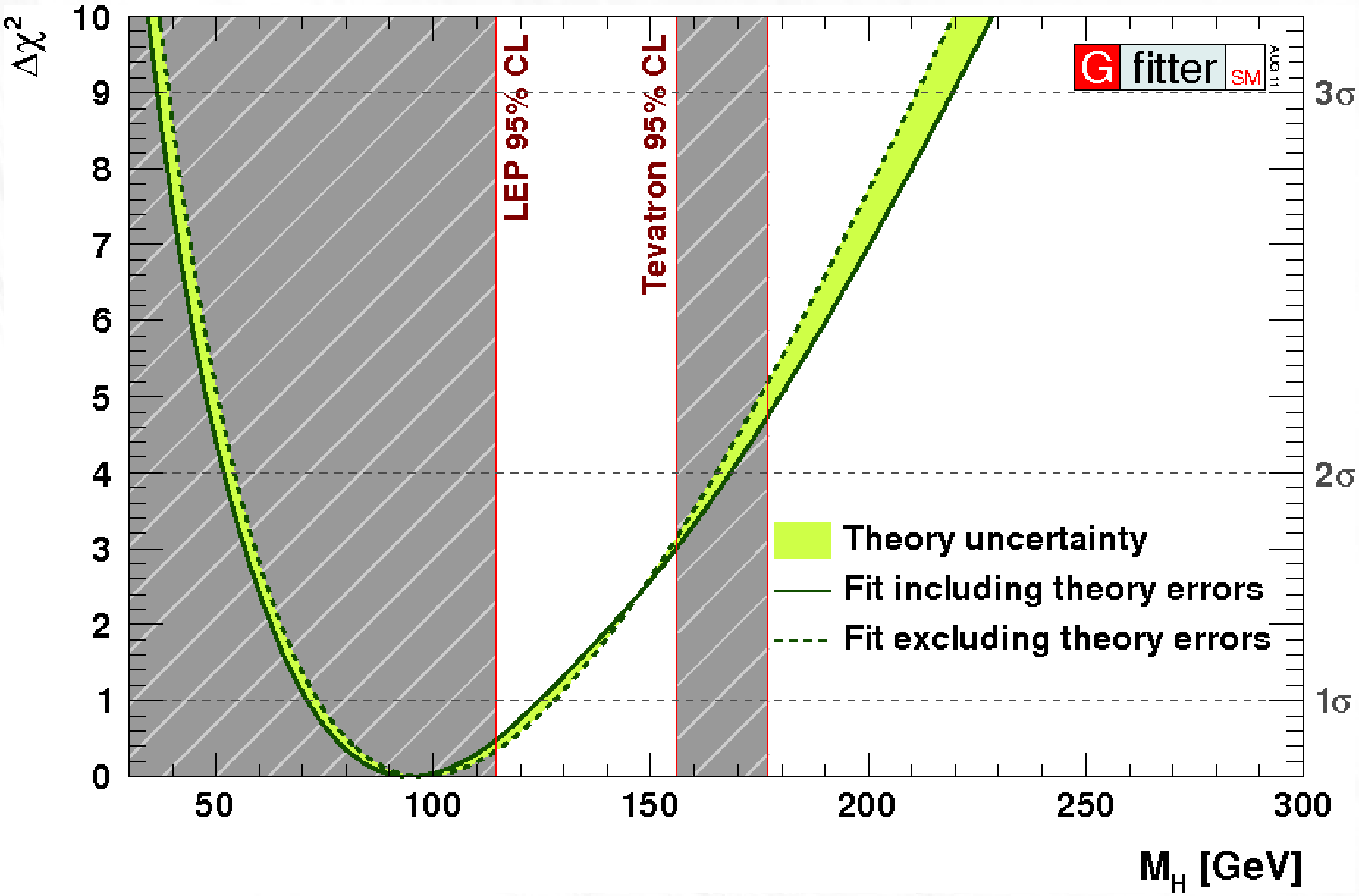
(Indirect) bounds on Higgs Mass



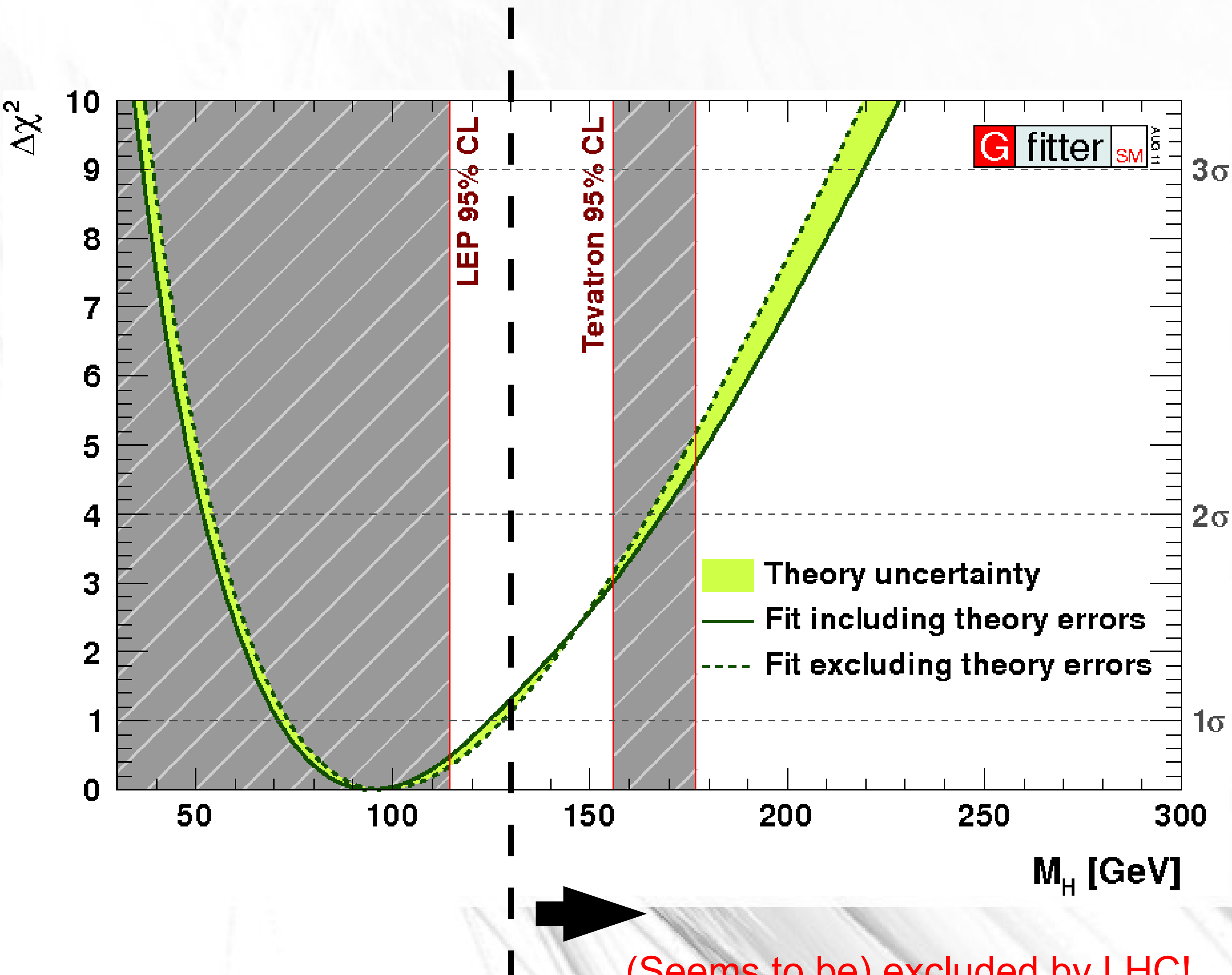


ZFITTER
The Fortran Package ZFITTER

(Indirect) bounds on Higgs Mass



(Indirect) bounds on Higgs Mass

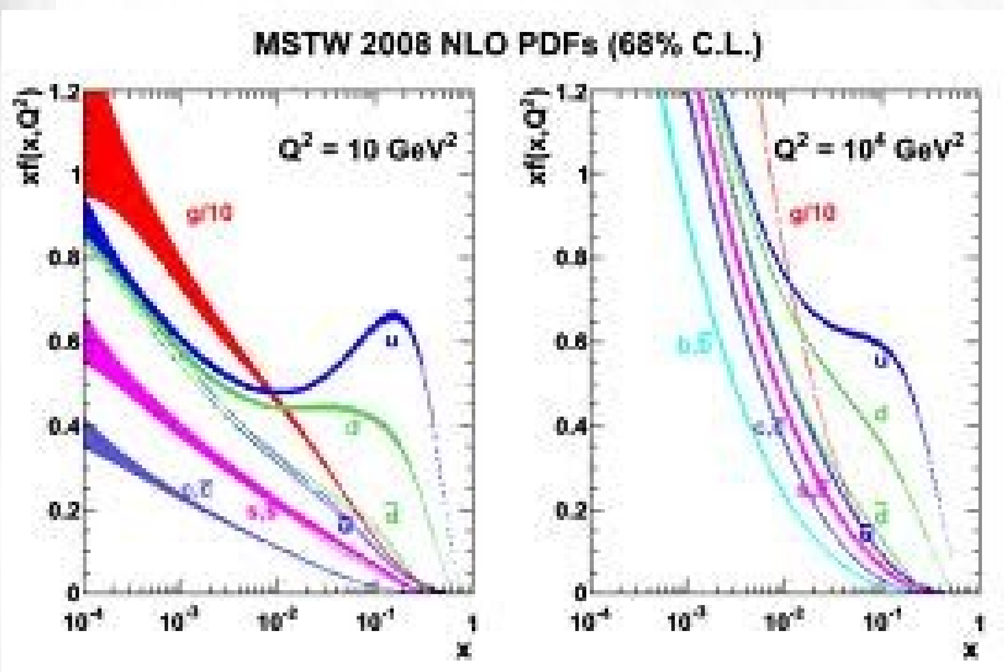


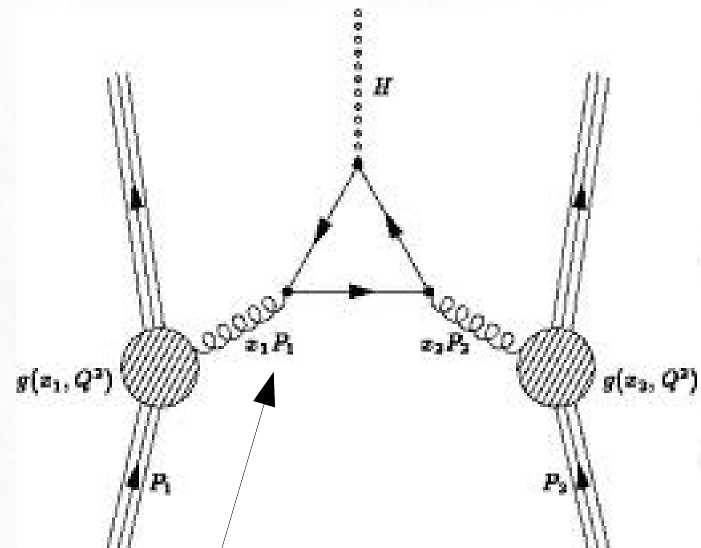
(Seems to be) excluded by LHC!

More on importance of Loop corrections

Some processes in the SM are ONLY due to loops!

Very important to the LHC Higgs searches



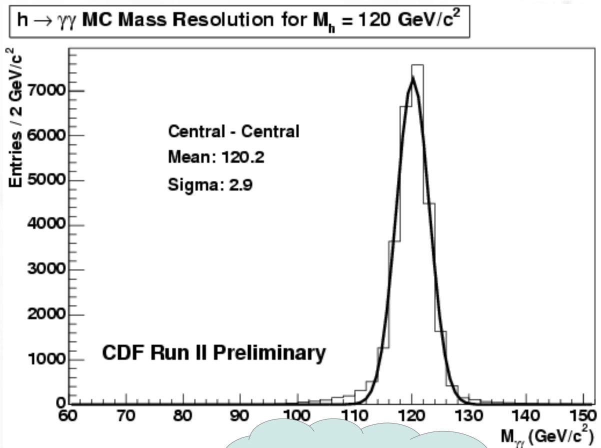


Since we expect that M_h<<1 TeV, x should be small

The missing piece: Higgs particle

- Higgs mass is a free parameter of the SM!

Should be measured in a direct experiment
(e.g. as a Peak in some disrtibution)

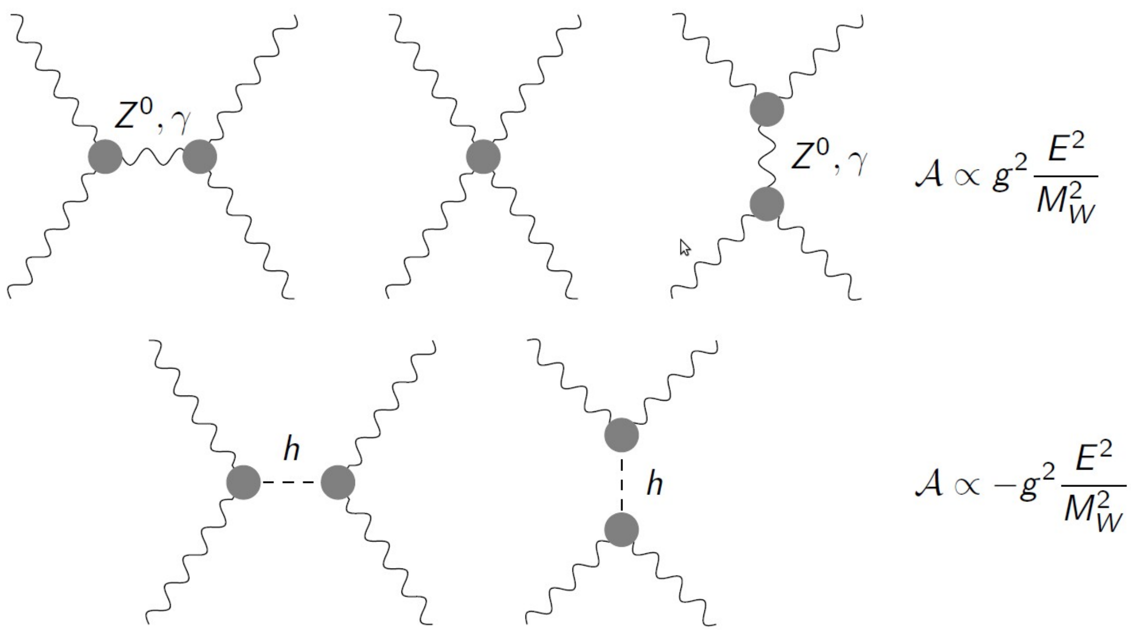


- But we have indirect bounds
  - from precision corrections
  - from theoretical consistency

Theoretical constraints on the Higgs boson mass

- Unitarity problem in WW → WW scattering

Longitudinal polarization of W-boson



Without Higgs WW scattering violate unitarity (cross-section grows with energy)

TeV scale favoured

Theoretical constraints on the Higgs boson mass

- Triviality and Stability

$$M_H^2 = 2\lambda v^2$$

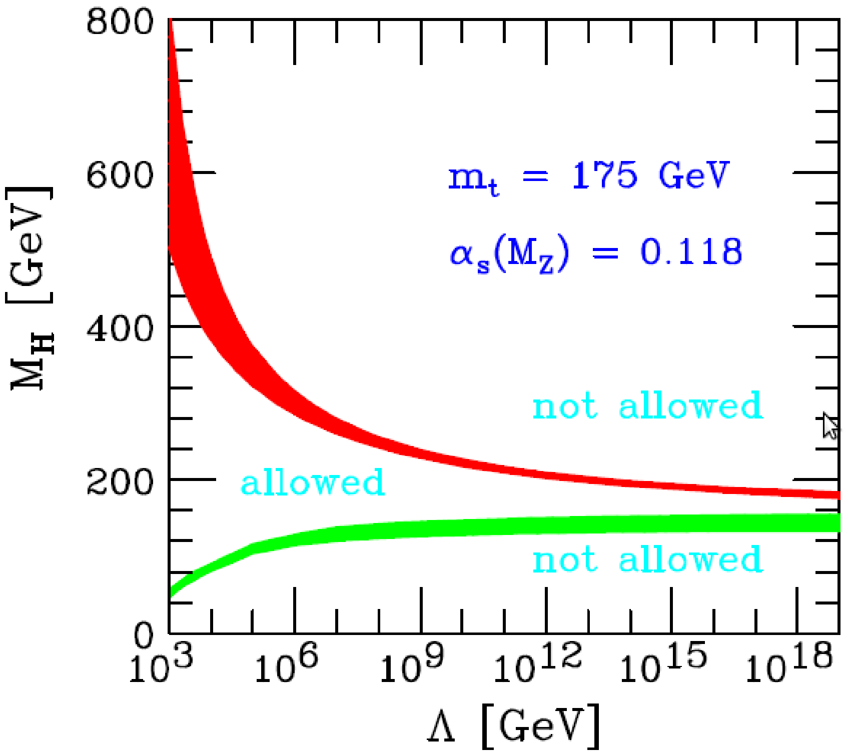
$$\frac{d\lambda}{dt} = \frac{1}{16\pi^2}\left(12\lambda^2 - 3\,g_t^4 + 6\,\lambda\,g_t^2 + \cdots\right)$$

For large M_H:

$$\lambda(Q) = \frac{M_H^2}{2v^2 - \frac{3}{2\pi^2} M_H^2 \ln\frac{Q}{v}}$$

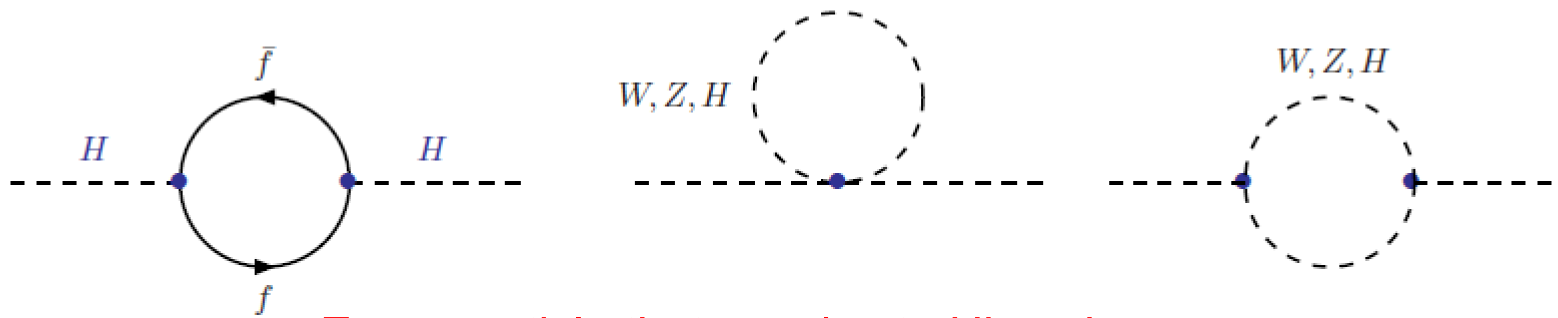
For small M_H:

$$\lambda(Q) = \lambda(v) - \frac{\frac{3}{8\pi^2} y_t^4(v)\ln\frac{Q}{v}}{1 - \frac{9}{16\pi^2} y_t^2(v)\ln\frac{Q}{v}}$$



Theoretical constraints on the Higgs boson mass

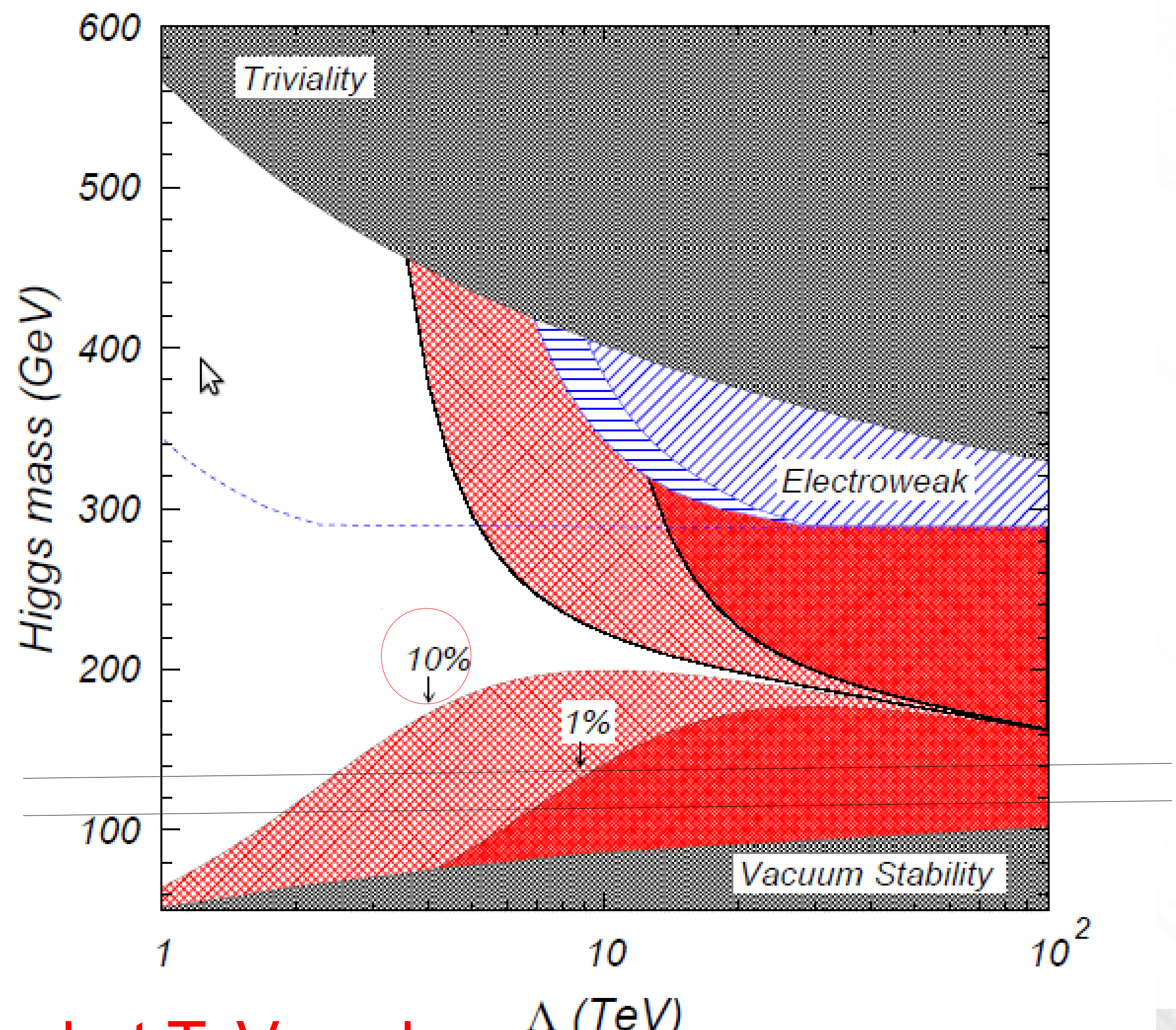
- Naturalness (hierarchy problem)
  - No **symmetry** to protect the Higgs mass from large radiative corrections (scalar particle)



Every particle that couples to Higgs boson
give contribution proportional
to ITS mass squared

NB: For vector bosons: gauge symmetry, for fermions — chiral symmetry

Theoretical constraints on the Higgs boson mass



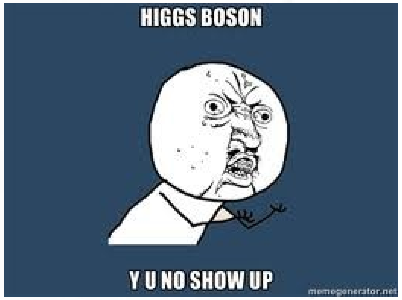
$$M_H \sim \mathcal{F}\delta M_H(\Lambda)$$

New Physics expected at TeV scale

Issues of the SM

- Higgs is missing (EWSB mehanism)
- No Dark Matter candidate
- Gauge coupling unification is problematicty
- Large number of free parameters
- Flavor problem
- Gravity?
- ….

Issues of the SM



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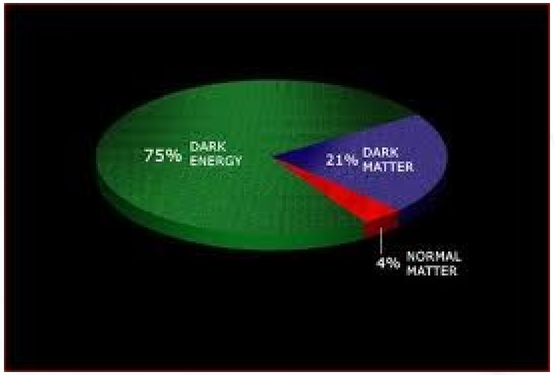
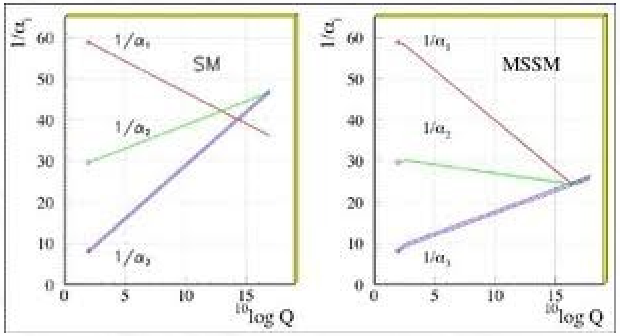


- Flavor problem
- Gravity?



- ….

Lecture 4 summary

- The SM exhibits (almost) **perfect** agreement with data in High Energy Physics experiments!
- Possible New Physics **HAS** to reproduce it as a low-energy effective theory!
- Still, there are some issues that prevent us from saying that the SM is the unltimate theory
- We are waiting for NEW data from LHC to find the last ingridient of the model — the Higgs boson (test the EWSB mechansm).

Topics NOT covered in the lectures

- QCD

  (A.V. Nesterenko, O.V. Teryaev)
- Flavor Physics in Lepton sector

  (V.A. Naumov and S.M. Bilenky)
- Renormalization

  (A.A. Vladimirov)
- Top Physics
- ….

Thank you!