Physics mit Schmaltz

Lecture II

Locality: can expand $\mathcal{L}$ in power series in ϕ, ψ, ∂_μ

$$\mathcal{L} = c_0 M^4 + c_2 M^2 H^\dagger H + M \mathcal{L}_3 + \mathcal{L}_4 + \frac{\mathcal{L}_5}{M} + \frac{\mathcal{L}_6}{M^2} + \cdots$$

mass dimensions: $[\partial_\mu] = 1$ $\quad [\mathcal{L}] = 4$

$[\phi] = 1$ $\quad [\psi] = 3/2$

$[M] = 1$ $\longleftarrow$ some UV mass scale

Examine dimensionless couplings first $\mathcal{L}_4$

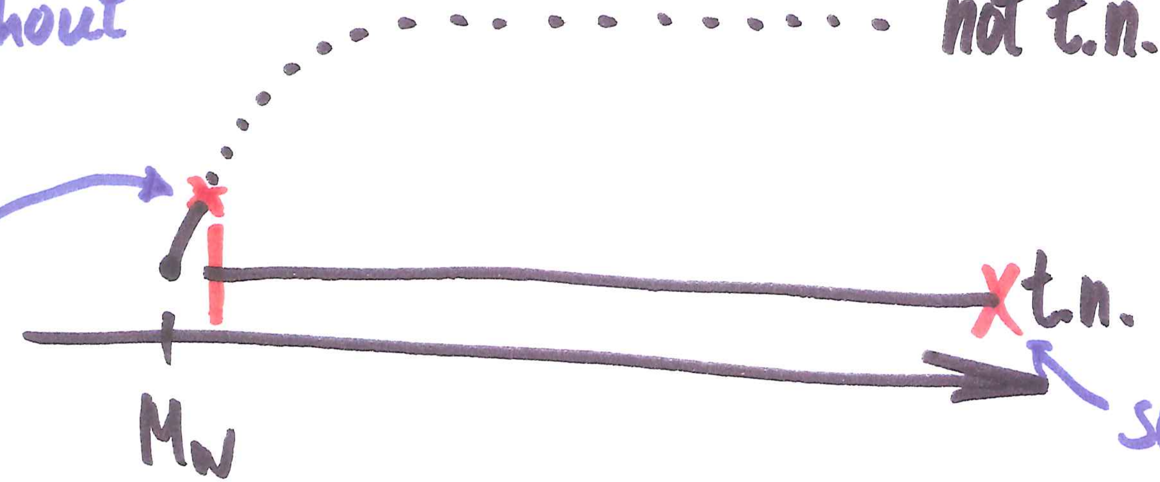
$$\mathcal{L}_4^{toy} \sim (\partial\phi)^2 + \lambda^2\phi^4 + \bar{\psi}\not{\partial}\psi + \lambda_t\phi\bar{\psi}\psi$$

What is the theoretically natural/expected size for the couplings λ, λ_t ?

(at the weak scale)

for a technically natural coupling the mechanism which explains smallness can be in the far UV

in the case without tech.nat. the mechanism must be in the IR



some UV mechanism, not accessible

$\Rightarrow$ accessible to experiment!

a coupling which is not tech.nat. is good news for experiment.

in $\mathcal{L}_4^{SM}$ all* couplings are tech. nat.

☹ no sign of N.P. nearby.

λ_{quarks}, $\lambda_{leptons}$ chiral symmetry

g_s, g, g' gauge symmetry

$\lambda_{Higgs} \sim 0.1$ no new symmetry in $\lambda_H \to 0$ limit but λ_H has natural size in SM

$\delta\lambda_{Higgs} \sim 0.1$

the rest of the SM Lagrangian ...

$$c_0 M^4 + c_2 M^2 H^\dagger H + \mathcal{L}_4 + \underbrace{\frac{\mathcal{L}_5}{M} + \frac{\mathcal{L}_6}{M^2}}_{\text{tomorrow}} + \cdots$$

cosmo const.

Higgs mass term

is $m^2 H^\dagger H$ tech. nat?

symmetry: $H \to H + \text{const}$ can forbid $m^2 H^\dagger H$

but: broken badly by other couplings $\lambda_t Q H u^c$

$\lambda^2 H^4$

$g^2 W_\mu W^\mu H^2$

how about scale invariance symmetry?

$$\phi \to s\,\phi(sx)$$

$$\psi \to s^{3/2}\,\psi(sx)$$

equivalent to

$$\phi \to s\,\phi(x)$$

$$\psi \to s^{3/2}\,\psi(x)$$

$$d^4x \to \frac{1}{s^4}\,d^4x$$

$$\partial \to s\,\partial$$

Scale invariance and the Higgs

SM approximately
scale inv't near M_{weak}

broken by $m_H^2 H^\dagger H$

$g(\mu/M)$

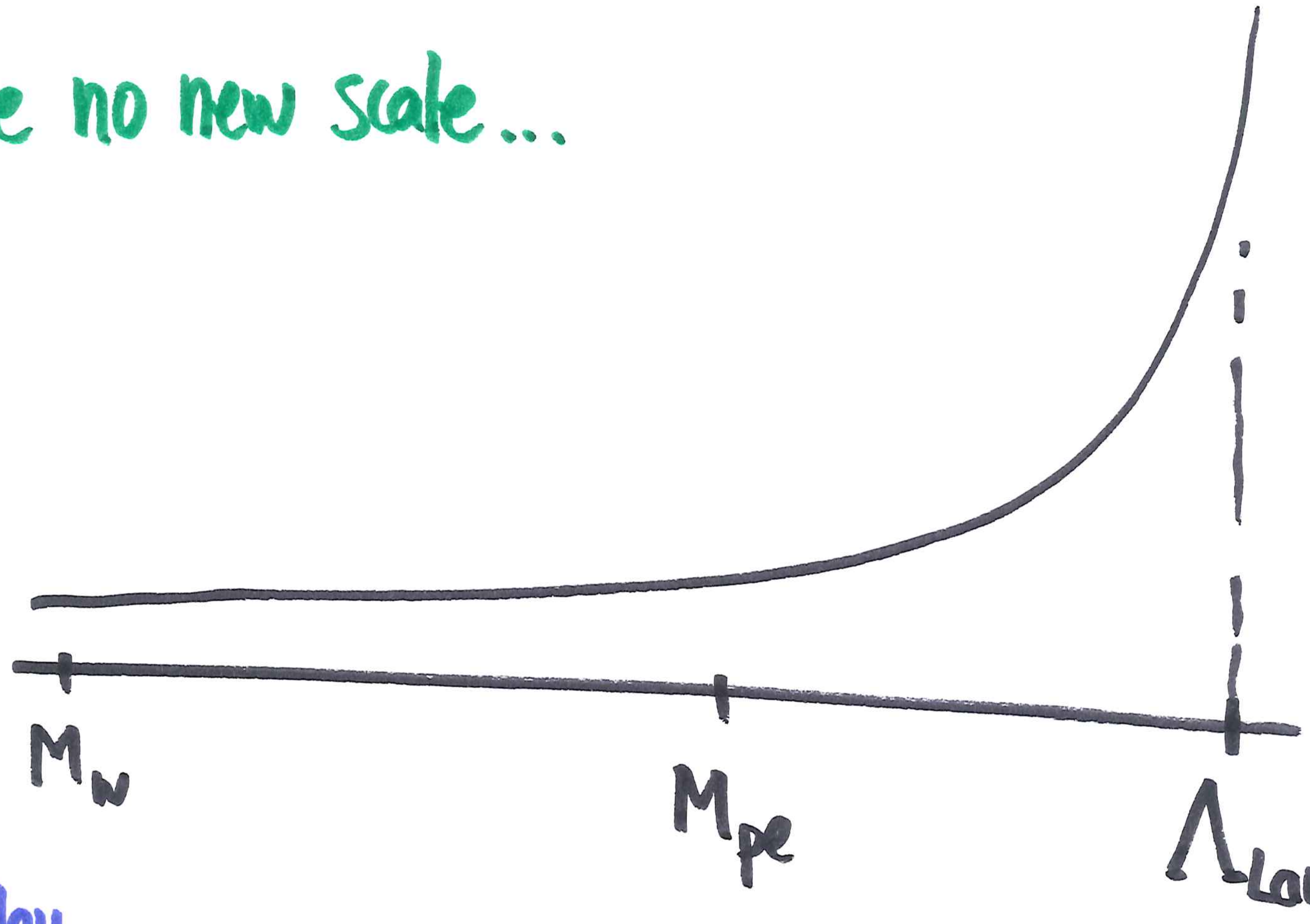
$$\frac{d}{d\ln\mu} m_H^2 \propto m_H^2 \frac{g^2}{16\pi^2} \cdots$$

technically natural
in IR effective theory

problem: SI must be strongly broken (in UV)

($\Longrightarrow$ cannot be used to argue that m_H is natural)

why? assume no new scale...



$\delta m_H^2 \sim \Lambda_{Landau}^2$

this problem does not occur for λ_{up}

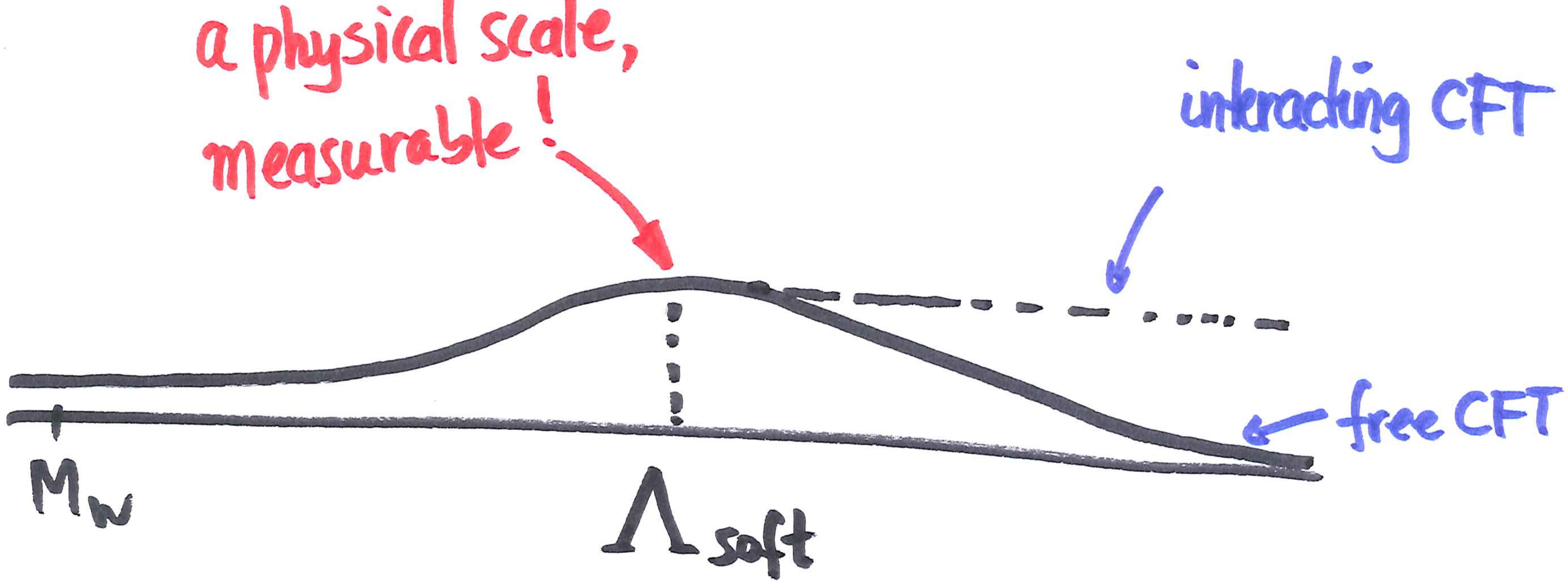
i.e. there is no coupling getting large and breaking $u^c \to e^{i\theta} u^c$ symmetry

$\lambda_{up} \, Q H u^c$

consistent to assume no large chiral symmetry violation in UV

not consistent to assume no scale violation in UV

must "soften" interactions



$$m_H^2 \propto \Lambda_{soft}^2 \implies \Lambda_{soft} \lesssim \frac{4\pi}{g'} m_H \rightarrow \text{LHC}$$

or fine-tuning ☹

final points:

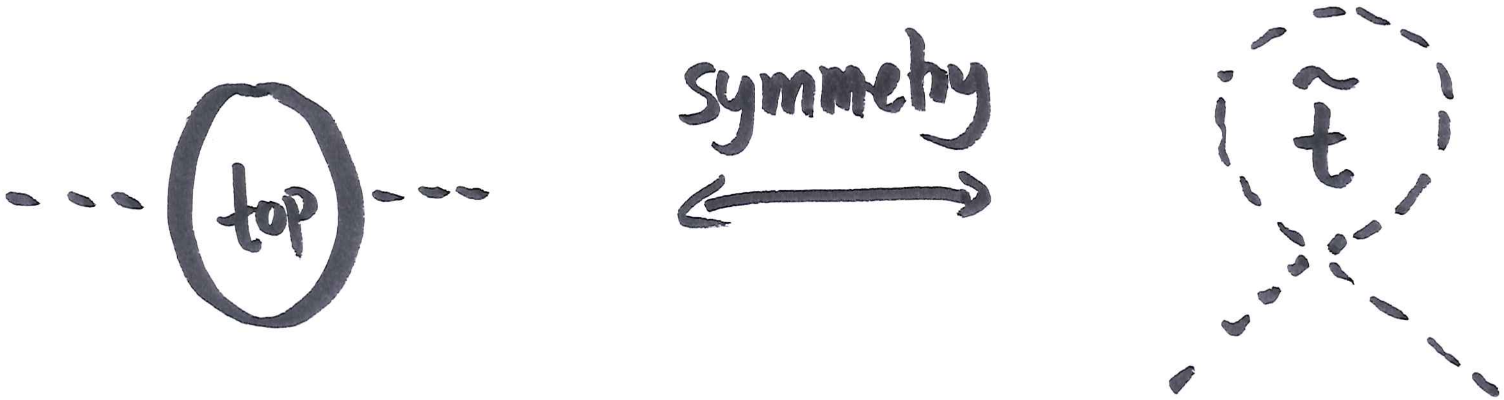
Λ_{soft} ? embed $U(1)_Y$ in non-Abelian group

M_{pl} ? perhaps QFT does not apply to gravity ... desperate ... I know...

other symmetries that can make Higgs mass (technically) natural:

- SUSY $\quad H \leftrightarrow \psi$
- Shift-(Goldstone)-sy. $\quad H \to H + \text{const}$
- Combinations (twin, ...)

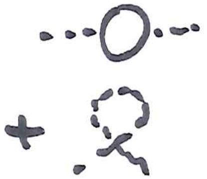
"partner" symmetries



UV-sensitive cancels $\widetilde{\text{UV-sensitive}}$

$$\delta m_H^2 \sim m_{\tilde{t}}^2 \, \frac{\lambda_t^2}{16\pi^2}$$

e.g. SUSY



$$\Rightarrow \quad \delta m_H^2 = -\frac{3}{4\pi^2}\lambda_t^2 \, m_{\tilde t}^2 \left(\log \frac{\Lambda_{UV}}{m_{\tilde t}}\right)$$

$$\left| \frac{\delta m_H^2}{m_H^2} \right| \simeq 40 \left[\frac{m_{\tilde t}}{\text{TeV}}\right]^2 \left[\frac{\log\left(M_{UV}/m_{\tilde t}\right)}{10}\right]$$

125 GeV

somewhat tuned ... similar in all other known partner models

the SM Lagrangian

$$c_0 M^4 + c_2 M^2 H^\dagger H + \mathcal{L}_4 + \frac{\mathcal{L}_5}{M} + \frac{\mathcal{L}_6}{M^2} + \cdots$$

only 1 term allowed: $\dfrac{(HL)^2}{10^{14}\,\text{GeV}}$ or Dirac neutrino mass λHLN^c

Optimistic: new physics @ few TeV $\equiv M$

(probably coupled to Higgs $\leftrightarrow$ naturally)

integrate out ...

$$\mathcal{L}_6 \sim \frac{H^\dagger D_\mu H \, H^\dagger D^\mu H}{M^2} + \frac{H^\dagger D_\mu H \, \bar{e}_R \gamma^\mu e_R}{M^2} + \frac{H^\dagger \sigma^a H \, W^a_{\mu\nu} B^{a\mu\nu}}{M^2} + \mathcal{L}_7 + \mathcal{L}_8 + \dots$$

$$+ \frac{H^\dagger H \, B^{\mu\nu} B_{\mu\nu}}{M^2} + \frac{H^\dagger H \, W^a_{\mu\nu} W^{a\mu\nu}}{M^2} + >100 \text{ more at dim 6}$$

predictive? 

$+$  $\sim \frac{1}{q^2} + \frac{1}{M^2} = \frac{1}{q^2}\left(1 + \frac{q^2}{M^2}\right)$ expansion in q^2/M^2

most violate flavor symmetries

e.g. $\frac{(\bar{d}_L \gamma_\mu s_L)^2}{M^2} + h.c.$ complex ϵ_K: $M \gtrsim 10^4$ TeV

real Δm_K: $\gtrsim 10^3$ TeV

$(\bar{c} u)^2$ $D\text{-}\bar{D}$: $\gtrsim 10^3$ TeV

$(\bar{d} b)$ $B\text{-}\bar{B}$: $\gtrsim 3 \cdot 10^2$ TeV

$(\bar{s} b)$ $B_s \bar{B}_s$: $\gtrsim 10^2$ TeV

assume minimal flavor violation – tech. nat.

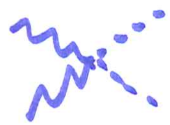
A Higgs physics example

$$\mathcal{L}_6 \sim c_1 g'^2 \frac{H^\dagger H B_{\mu\nu} B^{\mu\nu}}{M^2} + c_2 g^2 \frac{H^\dagger H W^a_{\mu\nu} W^{a\,\mu\nu}}{M^2} + c_{12} g g' \frac{H^\dagger \sigma^a H W^a_{\mu\nu} B^{\mu\nu}}{M^2}$$

plug in $\langle H \rangle$: $H = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v+h \end{pmatrix}$

expand... $v^2 F_{\mu\nu}^2 + vh F_{\mu\nu}^2 + h^2 F_{\mu\nu}^2$

PEW $\qquad$ $h \to V_\mu V^\mu$



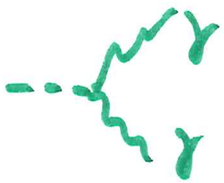
$$\to \underbrace{c_1 g'^2 \frac{v^2}{2M^2} B_{\mu\nu}B^{\mu\nu} + c_2 g^2 \frac{v^2}{2M^2} W^a_{\mu\nu}W_a^{\mu\nu}}_{\text{corrections to } SU(2)\times U(1) \text{ kinetic terms,}} + \underbrace{c_{12}\, g g' \frac{v^2}{2M^2} W^3_{\mu\nu}B^{\mu\nu}}_{SU(2) \text{ breaking } Z\text{-}\gamma \text{ mixing}}$$

rescale $B_\mu, W^a_\mu \Rightarrow$ redefine g, g'

$$\text{"}S\text{"} \equiv 16\pi c_{12} \frac{v^2}{M^2}$$

$$+ \underbrace{c_1 g'^2 \frac{v^2}{M^2}\frac{h}{v} B_{\mu\nu}^2 + c_2 g^2 \frac{v^2}{M^2}\frac{h}{v}(W^a_{\mu\nu})^2 + c_{12}\, g g' \frac{v^2}{M^2}\frac{h}{v} W^3_{\mu\nu}B^{\mu\nu}}$$

$$= \underbrace{4e^2\frac{v^2}{M^2}(c_1+c_2+c_{12})}_{\equiv c_{\gamma\gamma}e^2} \frac{h}{v}\frac{F_{\mu\nu}^2}{4} + \underbrace{\ldots}_{c_{\gamma Z}} \frac{h}{v} F_{\mu\nu}Z^{\mu\nu} + \underbrace{\ldots}_{c_{ZZ}} \frac{h}{v} Z_{\mu\nu}Z^{\mu\nu}$$

Higgs decays: 

γZ $\qquad$ ZZ^*

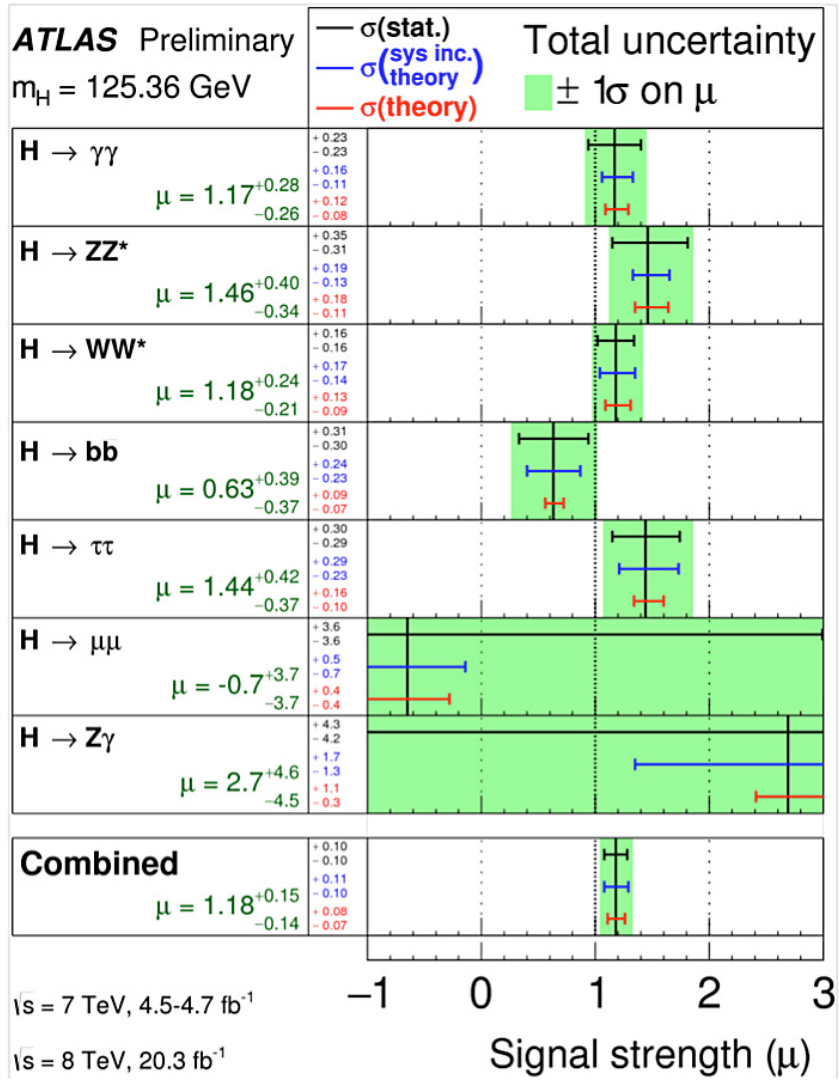
PDG 2015:
Z-pole

Quantity	Value	Standard Model	Pull
M_Z [GeV]	91.1876 ± 0.0021	91.1880 ± 0.0020	-0.2
Γ_Z [GeV]	2.4952 ± 0.0023	2.4955 ± 0.0009	-0.1
$\Gamma(\text{had})$ [GeV]	1.7444 ± 0.0020	1.7420 ± 0.0008	—
$\Gamma(\text{inv})$ [MeV]	499.0 ± 1.5	501.66 ± 0.05	—
$\Gamma(\ell^+\ell^-)$ [MeV]	83.984 ± 0.086	83.995 ± 0.010	—
σ_{had}[nb]	41.541 ± 0.037	41.479 ± 0.008	1.7
R_e	20.804 ± 0.050	20.740 ± 0.010	1.3
R_μ	20.785 ± 0.033	20.740 ± 0.010	1.4
R_τ	20.764 ± 0.045	20.785 ± 0.010	-0.5
R_b	0.21629 ± 0.00066	0.21576 ± 0.00003	0.8
R_c	0.1721 ± 0.0030	0.17226 ± 0.00003	-0.1
$A_{FB}^{(0,e)}$	0.0145 ± 0.0025	0.01616 ± 0.00008	-0.7
$A_{FB}^{(0,\mu)}$	0.0169 ± 0.0013		0.6
$A_{FB}^{(0,\tau)}$	0.0188 ± 0.0017		1.6
$A_{FB}^{(0,b)}$	0.0992 ± 0.0016	0.1029 ± 0.0003	-2.3
$A_{FB}^{(0,c)}$	0.0707 ± 0.0035	0.0735 ± 0.0002	-0.8
$A_{FB}^{(0,s)}$	0.0976 ± 0.0114	0.1030 ± 0.0003	-0.5
$\bar{s}_\ell^2$	0.2324 ± 0.0012	0.23155 ± 0.00005	0.7
	0.23176 ± 0.00060		0.3
	0.2297 ± 0.0010		-1.9
A_e	0.15138 ± 0.00216	0.1468 ± 0.0004	2.1
	0.1544 ± 0.0060		1.3
	0.1498 ± 0.0049		0.6
A_μ	0.142 ± 0.015		-0.3
A_τ	0.136 ± 0.015		-0.7
	0.1439 ± 0.0043		-0.7
A_b	0.923 ± 0.020	0.9347	-0.6
A_c	0.670 ± 0.027	0.6676 ± 0.0002	0.1
A_s	0.895 ± 0.091	0.9356	-0.4

PDG 2015:
non-Z-pole

Quantity	Value	Standard Model	Pull
m_t [GeV]	173.24 ± 0.95	173.87 ± 0.87	-0.7
M_W [GeV]	80.387 ± 0.016	80.363 ± 0.006	1.5
	80.376 ± 0.033		0.4
Γ_W [GeV]	2.046 ± 0.049	2.090 ± 0.001	-0.9
	2.196 ± 0.083		1.3
M_H [GeV]	125.6 ± 0.4	125.5 ± 0.4	0.1
$\rho_{\gamma W}$	0.45 ± 0.31	0.01 ± 0.03	1.4
	0.12 ± 0.43	0.00 ± 0.03	0.3
$\rho_{\gamma Z}$	0.08 ± 0.28	0.01 ± 0.04	0.2
ρ_{ZW}	0.30 ± 0.39	0.00 ± 0.01	0.8
$g_V^{\nu e}$	-0.040 ± 0.015	-0.0397 ± 0.0001	0.0
$g_A^{\nu e}$	-0.507 ± 0.014	-0.5064	0.0
$Q_W(e)$	-0.0403 ± 0.0053	-0.0473 ± 0.0003	1.3
$Q_W(p)$	0.064 ± 0.012	0.0708 ± 0.0003	-0.6
$Q_W(\mathrm{Cs})$	-72.62 ± 0.43	-73.25 ± 0.01	1.5
$Q_W(\mathrm{Tl})$	-116.4 ± 3.6	-116.90 ± 0.02	0.1
$\widehat{s}^2_Z(\mathrm{eDIS})$	0.2299 ± 0.0043	0.23126 ± 0.00005	-0.3
τ_τ [fs]	291.13 ± 0.43	291.19 ± 2.41	0.0
$\frac{1}{2}(g_\mu - 2 - \frac{\alpha}{\pi})$	$(4511.07 \pm 0.79) \times 10^{-9}$	$(4508.68 \pm 0.08) \times 10^{-9}$	3.0

ATLAS Run1: Signal strength

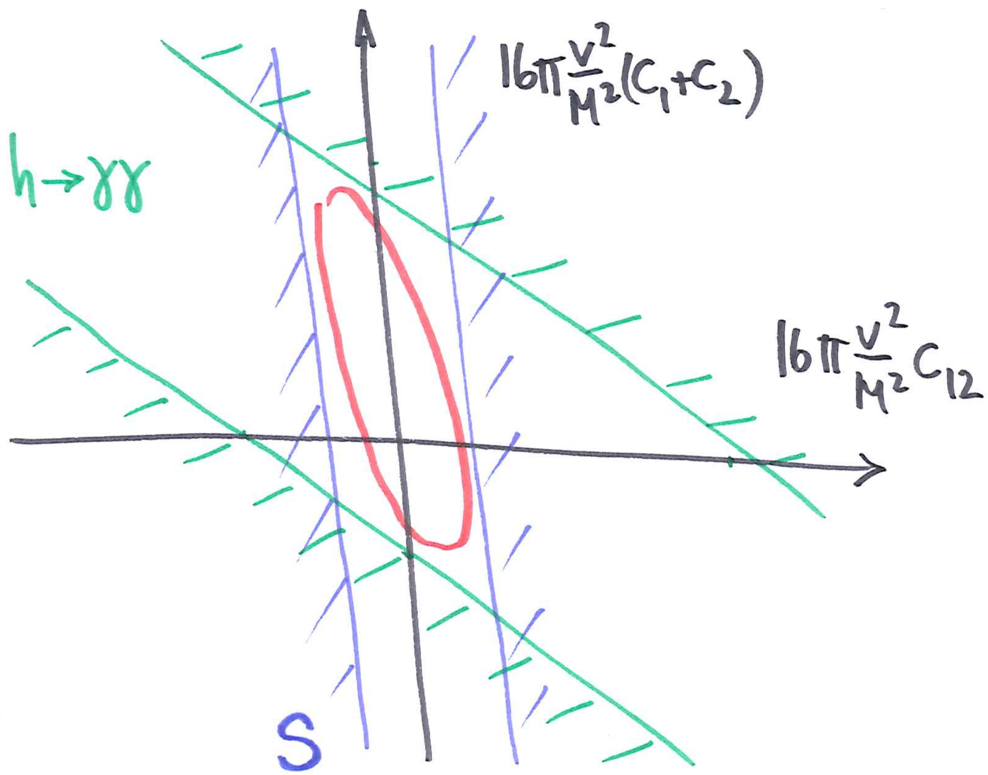


the data :
(@ 95%)

- Precision electroweak $\quad S = -0.03 \pm 0.10$ PDG
- $h \to \gamma\gamma$ $\quad C_{\gamma\gamma} = 0.014 \pm 0.058$

Falkowski et al hep-ph/1505.00046

($h \to \gamma Z \quad C_{\gamma Z} < 0.2$)



Bound on M?

$$c_i = 1 \quad \Rightarrow M \gtrsim 6\,\text{TeV}$$

$$c_i = \frac{1}{16\pi^2} \quad \Rightarrow M \gtrsim 500\,\text{GeV}$$

We are pleased to announce the fourth Higgs Effective Field Theories workshop (HEFT2016) will take place at the Niels Bohr Institute at the University of Copenhagen from Wednesday 26th to Friday 28th October 2016. Pervious installments of the workshop were held at CERN (2013), Madrid (2014) and Chicago in 2015.