Electroweak Symmetry Breaking: To Higgs or not to Higgs

- Higgs mechanism. The Higgs as a UV moderator of EW interactions. Needs for New Physics beyond the Higgs.
- Review of possible scenarios :Gauge-Higgs Unification, Little Higgs, Composite Higgs, (5D) Higgsless models.

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A decade of experimental successes

- top discovery
- solar and atmospherical neutrino oscillations
- direct CP violation in the K system (d$\underline{s}$) (K-long decaying into 2 pions)
- CP violation in the B system (d$\underline{b}$)
- evidence of an accelerated phase in the expansion of the Universe
- measure of the dark energy/dark matter composition of the Universe

These results have strengthened the SM as a successful description of Nature at the quantum level ... but

... these experimental results also concluded that there is a physics beyond the Standard Model.

The questions addressed in these lectures

we expect new physics to play a crucial role in
the mechanism of electroweak symmetry breaking.

- What is the scale of new physics in the EWSB sector?
- What is the population of this new scale? Which particles?
- Which interactions?

Identifying the new spectroscopy should allow to decipher the organization principle that governs the EWSB sector

vector bosons ⟷ gauge principle

Higgs/EWSB sector ⟷ ?
strong dynamics, susy, xdims

Bounds on (Dangerous) New Physics

Heavy Particles ⇛ new interactions for SM particles

broken symmetry	operators	scale Λ
B, L	$(QQQL)/\Lambda^2$	10^{13} TeV
flavor (1,2$^{\rm nd}$ family), CP	$(\bar{d}s\bar{d}s)/\Lambda^2$	1000 TeV
flavor (2,3$^{\rm rd}$ family)	$m_b(\bar{s}\sigma_{\mu\nu}F^{\mu\nu}b)/\Lambda^2$	50 TeV

At colliders, it will be difficult to find direct evidence of new physics in these sectors...

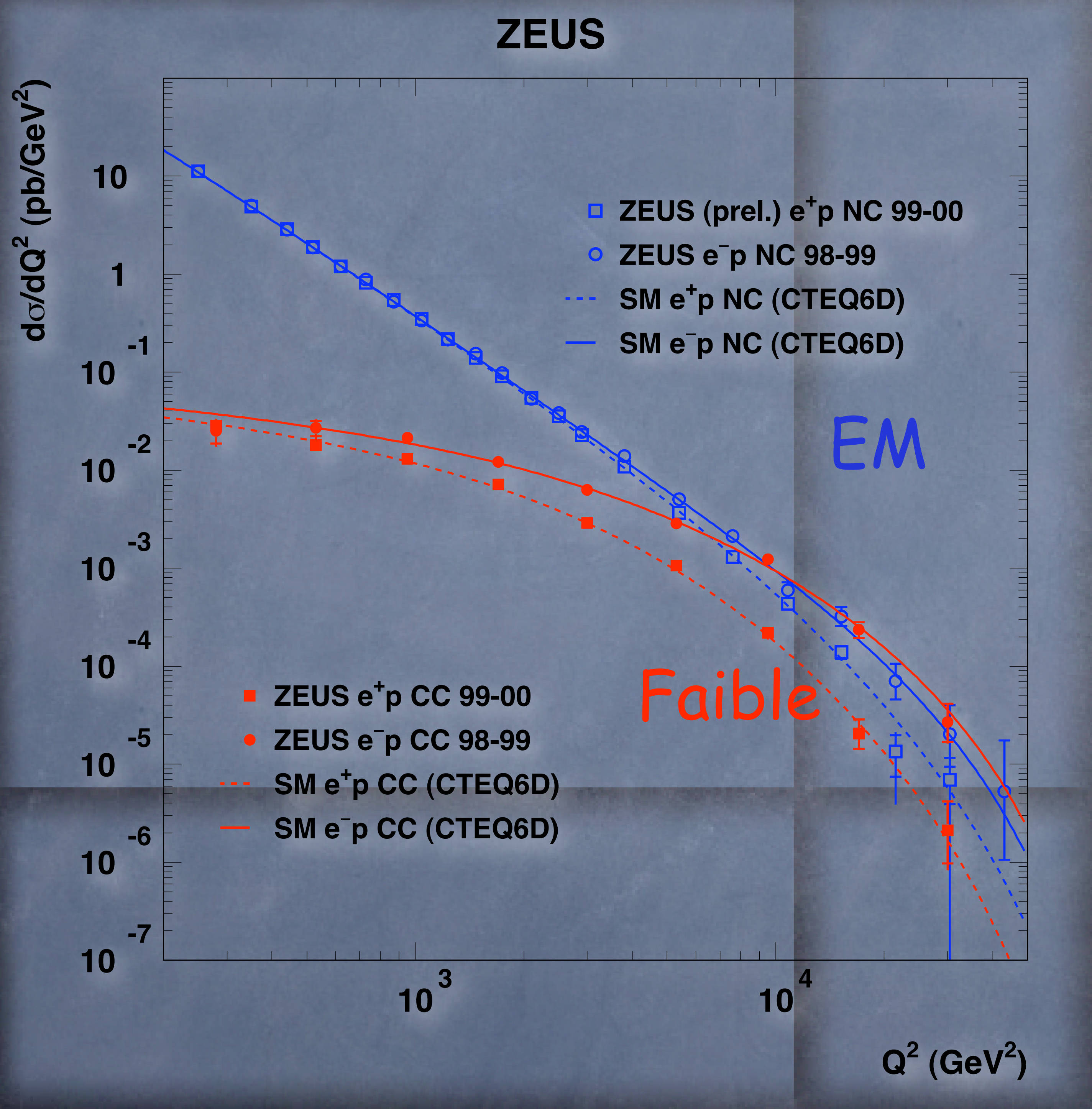
New Physics in the EW sector

$\left((h^\dagger\sigma^a h)W^a_{\mu\nu}B^{\mu\nu}\right)/\Lambda^2$	$\lvert h^\dagger D_\mu h\rvert^2/\Lambda^2$	$\left(h^\dagger h\right)^3/\Lambda^2$

$\Lambda \sim$ few TeV only

high potential for direct detection at LHC, ILC !!!

EW “unification” and EWSB



- Above ~ 100 GeV, electromagnetic and weak interactions are unified
- Below 100 GeV, γ and Z behave differently

$$m_\gamma < 6 \times 10^{-17}\ \mathrm{eV}$$

$$m_{W^\pm} = 80.425 \pm .038\ \mathrm{GeV}$$

$$m_{Z^0} = 91.1876 \pm .0021\ \mathrm{GeV}$$

The source of the Goldstone's

symmetry breaking: new phase with more degrees of freedom

massive W, Z: 3 physical polarizations=eaten Goldstone bosons

⇛ Where are these Goldstone's coming from? ⇚

common lore: from a scalar Higgs doublet

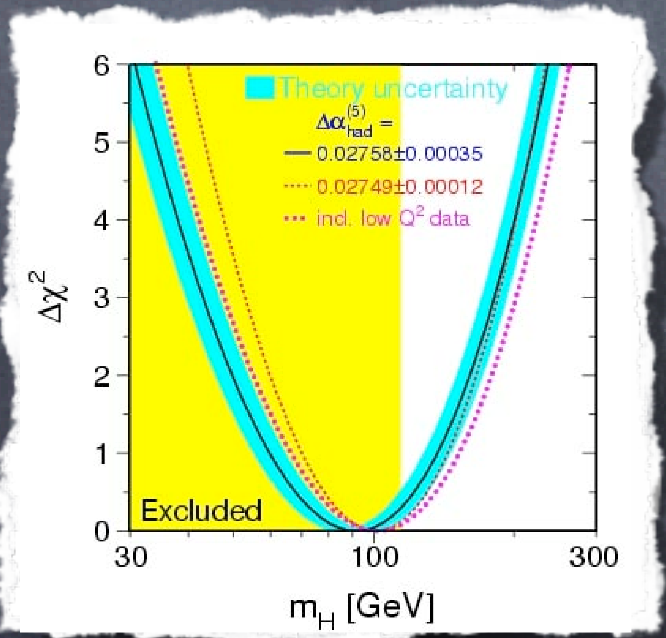
$$H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}$$

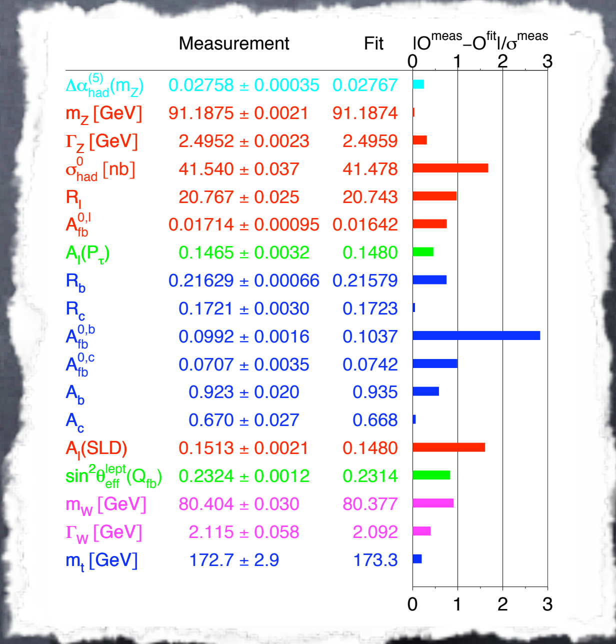
Higgs doublet = 4 real scalar fields

3 eaten Goldstone bosons ← → One physical degree of freedom the Higgs boson

Good agreement with EW data

(doublet ⇔ ρ=1)





	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ^0_{had} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.743
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01642
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1037
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1480
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.404 ± 0.030	80.377
Γ_W [GeV]	2.115 ± 0.058	2.092
m_t [GeV]	172.7 ± 2.9	173.3

But the Higgs hasn't been seen yet...

other origins of the Goldstone's: condensate of techniquarks, A5...

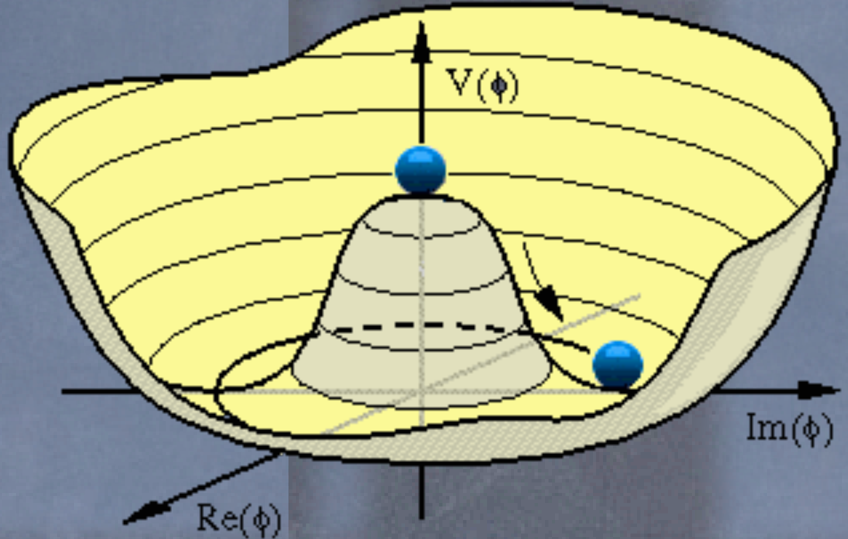
Higgs Mechanism

Symmetry of the Lagrangian

$$SU(2)_L \times U(1)_Y$$

Higgs Doublet

$$H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}$$



Symmetry of the Vacuum

$$U(1)_{e.m.}$$

Vacuum Expectation Value

$$\langle H \rangle = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix} \quad \text{with} \quad \mathrm{v} \approx 246\ \mathrm{GeV}$$

$$D_\mu H = \partial_\mu H - \frac{i}{2}\begin{pmatrix} gW^3_\mu + g'B_\mu & \sqrt{2}gW^+_\mu \\ \sqrt{2}gW^-_\mu & -gW^3_\mu + g'B_\mu \end{pmatrix} H \quad \text{with} \quad \mathrm{W}^\pm_\mu = \frac{1}{\sqrt{2}}\left(\mathrm{W}^1_\mu \mp \mathrm{W}^2_\mu\right)$$

$$|D_\mu H|^2 = \tfrac{1}{4}\, g^2 v^2\, W^+_\mu W^{-\,\mu} + \tfrac{1}{8}\left(W^3_\mu\, B_\mu\right)\begin{pmatrix} g^2v^2 & -gg'v^2 \\ -gg'v^2 & g'^2v^2 \end{pmatrix}\begin{pmatrix} W^{3\,\mu} \\ B^\mu \end{pmatrix}$$

- Gauge boson spectrum
  - electrically charged bosons $M_W^2 = \frac{1}{4}g^2v^2$
  - electrically neutral bosons

$$Z_\mu = cW^3_\mu - sB_\mu$$
$$\gamma_\mu = sW^3_\mu + cB_\mu$$

Weak mixing angle

$$c = \frac{g}{\sqrt{g^2+g'^2}}$$
$$s = \frac{g'}{\sqrt{g^2+g'^2}}$$

$$M_Z^2 = \frac{1}{4}(g^2+g'^2)v^2$$

$$M_\gamma = 0$$

Custodial Symmetry

- Rho parameter

$$\rho \equiv \frac{M_W^2}{M_Z^2 \cos^2\theta_w} = \frac{\frac{1}{4}g^2v^2}{\frac{1}{4}(g^2+g'^2)v^2\,\frac{g^2}{g^2+g'^2}} = 1$$

- Consequence of an approximate global symmetry of the Higgs sector

$H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}$ Higgs doublet = 4 real scalar fields

$V(H) = \lambda\left(H^\dagger H - \frac{v^2}{2}\right)^2$ is invariant under the rotation of the four real components

$$\boxed{SO(4) \sim SU(2)_L \times SU(2)_R}$$

$$SU(2)_R$$

$$\Downarrow$$

$$SU(2)_L \Rightarrow \begin{pmatrix} i\sigma^2 H^\star & H \end{pmatrix} = \Phi$$

2x2 matrix

$$\Phi^\dagger\Phi = H^\dagger H \begin{pmatrix} 1 & \\ & 1 \end{pmatrix}$$

$$V(H) = \frac{\lambda}{4}\left(\mathrm{tr}\Phi^\dagger\Phi - \mathrm{v}^2\right)^2$$

explicitly invariant under $SU(2)_L \times SU(2)_R$

Custodial Symmetry

Higgs vev

$$\langle H\rangle = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix} \qquad \langle \Phi\rangle = \frac{v}{\sqrt{2}} \begin{pmatrix} 1 & \\ & 1 \end{pmatrix}$$

$$SU(2)_L \times SU(2)_R \to SU(2)_V$$

unbroken symmetry in the broken phase

$(W^1_\mu, W^2_\mu, W^3_\mu)$ transforms as a triplet

$$(Z_\mu\, \gamma_\mu) \begin{pmatrix} M_Z^2 & 0 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} Z^\mu \\ \gamma^\mu \end{pmatrix} = (W^3_\mu\, B_\mu) \begin{pmatrix} c^2 M_Z^2 & -csM_Z^2 \\ -csM_Z^2 & s^2 M_Z^2 \end{pmatrix} \begin{pmatrix} W^{3\,\mu} \\ B^\mu \end{pmatrix}$$

The $SU(2)_V$ symmetry imposes the same mass term for all W^i thus $c^2 M_Z^2 = M_W^2$

ρ = 1

The hypercharge gauge coupling and the Yukawa couplings break the custodial SU(2)$_V$, which will generate a (small) deviation to ρ = 1 at the quantum level.

TH vs. EXP: importance of quantum corrections

How good is the agreement of the SM with exp. data?

SM has 3 parameters: g, g' and v (forgetting the fermions)

several observables

α (Coulomb potential), G_F (μ decay), m_Z, m_W, $s^2_{\rm eff}$ (LR asymmetry in Z decay), $\Gamma(Z \to l^+ l^-)$

g, g' and v are extracted from α, G_F and m_Z

$$\alpha = 1/137.03599911(46) \qquad G_F = 1.16637(1) \times 10^{-5}\ \text{GeV}^{-2} \qquad m_Z = 91.181876(21)\ \text{GeV}$$

and we can predict the values of other observables

theory at classical level

$$m_W = 80.839\ \text{GeV} \qquad s^2_{\rm eff} = 0.21215 \qquad \Gamma(Z \to l^+ l^-) = 84.841\ \text{MeV}$$

experiment (PDG'08)

$$m_W = 80.398 \pm 0.025\ \text{GeV} \qquad s^2_{\rm eff} = 0.23149 \pm 0.00013 \qquad \Gamma(Z \to l^+ l^-) = 83.984 \pm 0.086\ \text{MeV}$$

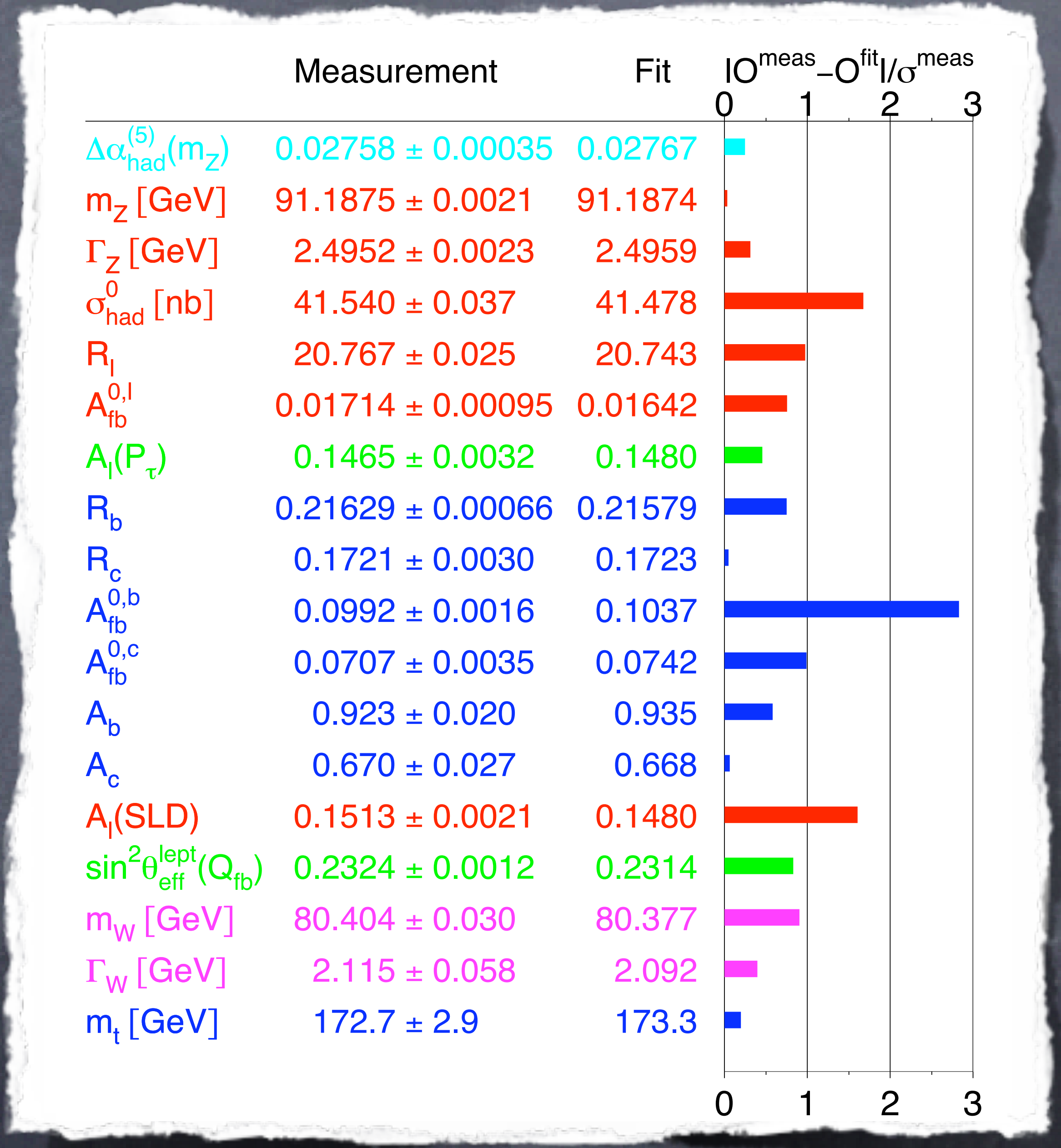
22 σ

150 σ

10 σ

TH vs. EXP: importance of quantum corrections

including quantum corrections, the agreement TH-EXP is better than 3σ for ~ 20 observables.



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computing these quantum corrections is technically challenging and beyond the scope of my lectures

$$H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}$$

Higgs doublet = 4 real scalar fields

3 eaten
Goldstone bosons

One physical degree of freedom
the Higgs boson

Higgs as a UV moderator

Why do we need a Higgs ?

The W and Z masses are inconsistent with the known particle content! Need more particles to soften the UV behavior of massive gauge bosons.

Indeed a massive spin 1 particle has 3 physical polarizations:

$$A_\mu = \epsilon_\mu \; e^{ik_\mu x^\mu}$$

$$\epsilon^\mu \epsilon_\mu = -1 \qquad k^\mu \epsilon_\mu = 0$$

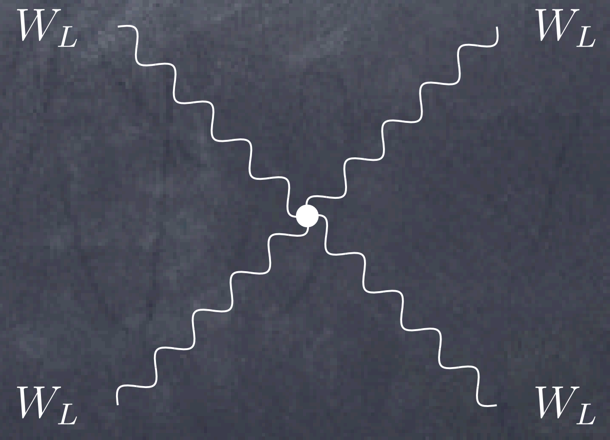
$$k^\mu = (E, 0, 0, k)$$

with $k_\mu k^\mu = E^2 - k^2 = M^2$

- 2 transverse: $\begin{cases} \epsilon_1^\mu = (0,1,0,0) \\ \epsilon_2^\mu = (0,0,1,0) \end{cases}$
- 1 longitudinal: $\epsilon_\perp^\mu = (\frac{k}{M}, 0, 0, \frac{E}{M}) \approx \frac{k^\mu}{M} + \mathcal{O}(\frac{E}{M})$

(in the R-ξ gauge, the time-like polarization ($\epsilon^\mu\epsilon_\mu = 1,\ k^\mu\epsilon_\mu = M$) is arbitrarily massive and decouple)

Bad UV behavior for the scattering of the longitudinal polarizations



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Bad UV behavior for
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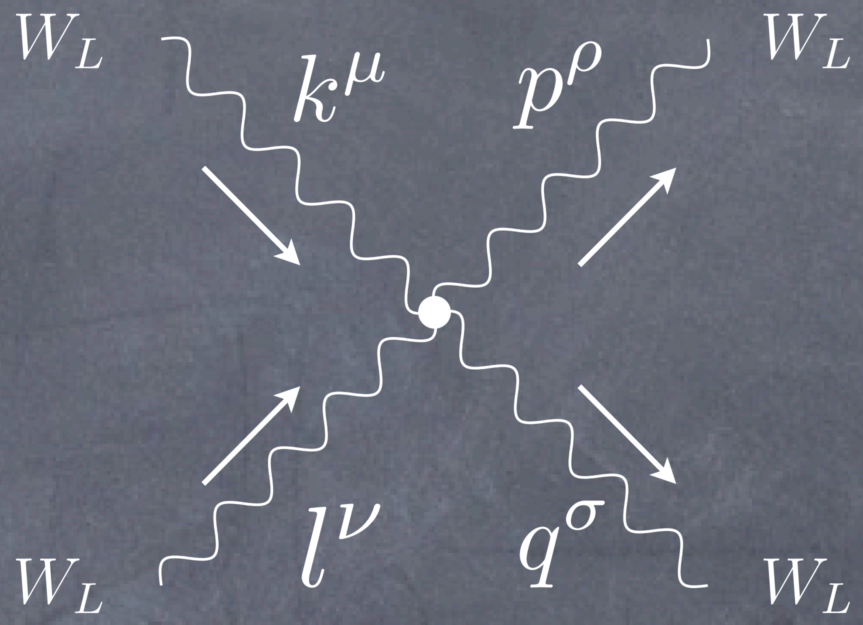


$$\mathcal{A} = \epsilon_l^\mu(k)\epsilon_l^\nu(l)\, ig^2(2\eta_{\mu\rho}\eta_{\nu\sigma} - \eta_{\mu\nu}\eta_{\rho\sigma} - \eta_{\mu\sigma}\eta_{\nu\rho})\, \epsilon_l^\rho(p)\epsilon_l^\sigma(q)$$

$$\mathcal{A} \propto g^2 \frac{E^4}{M^4}$$

violations of perturbative unitarity around E ~ M

A QCD antecedent

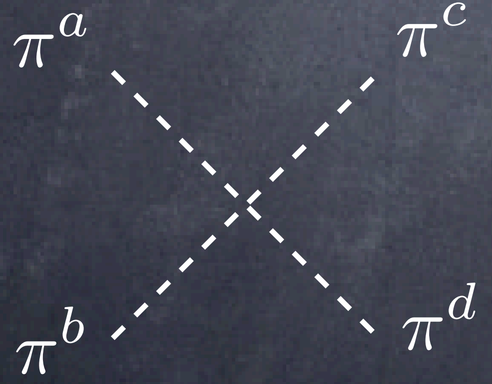
QCD pions are Goldstone bosons associated to $SU(2)_L \times SU(2)_R / SU(2)_V$

$$U = e^{i\pi^a\sigma^a/f_\pi} \begin{pmatrix} 0 \\ \frac{f_\pi}{\sqrt{2}} \end{pmatrix}$$

kinetic terms for U ⇔ interaction terms for π^a

$$\mathcal{L} = |\partial_\mu U|^2 = \frac{1}{2}(\partial_\mu \pi^a)^2 - \frac{1}{6f_\pi^2}\left((\pi^a\partial_\mu\pi^a)^2 - (\pi^a)^2(\partial_\mu\pi^a)^2\right) + \dots$$

contact interaction growing with energy



$$\mathcal{A}\left(\pi^a\pi^b \to \pi^c\pi^d\right) = \mathcal{A}(s,t,u)\delta^{ab}\delta^{cd} + \mathcal{A}(t,s,u)\delta^{ac}\delta^{bd} + \mathcal{A}(u,t,s)\delta^{ad}\delta^{bc}$$

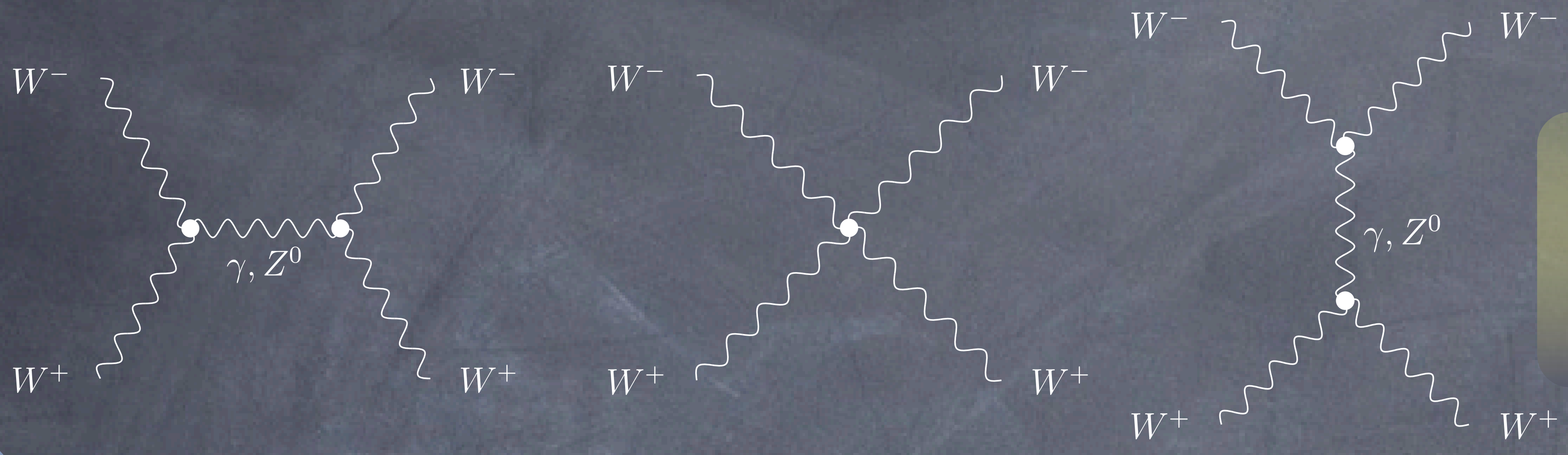
$$\mathcal{A}(s,t,u) = \frac{s}{f_\pi^2}$$

$f_\pi = 93 \text{ MeV}$ ⇒ unitarity bound

$$\sqrt{s} \sim 4\sqrt{\pi} f_\pi = 660 \text{ MeV}$$

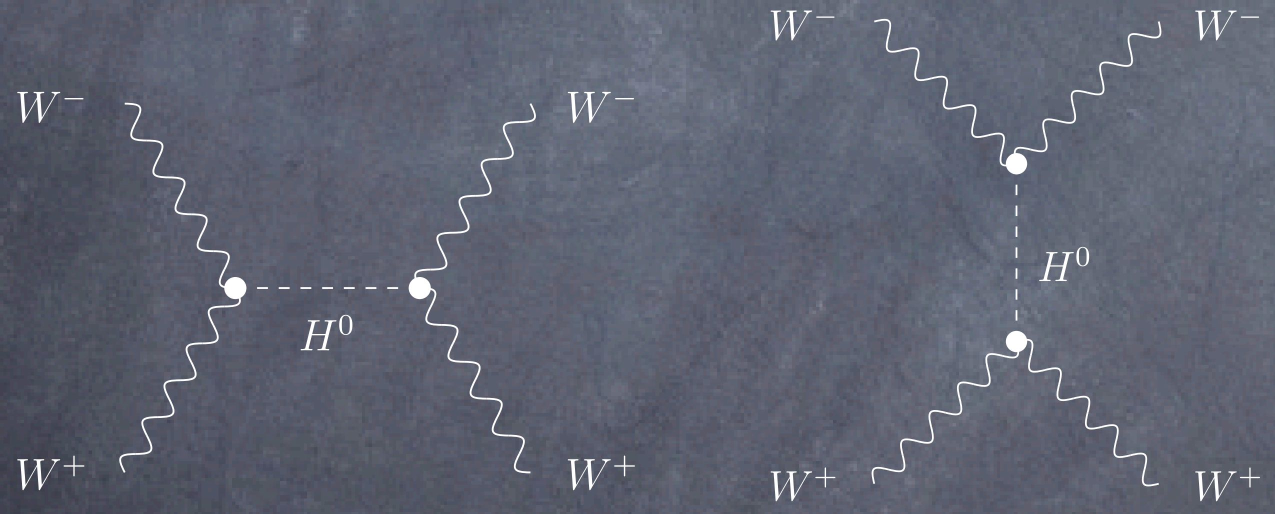
rho meson (m=770 MeV) is restoring unitarity

Why do we need a Higgs ?



$$\mathcal{A} = g^2 \left(\frac{E}{M_W} \right)^2$$

+



+

$$\mathcal{A} = -g^2 \left(\frac{E}{M_W} \right)^2$$

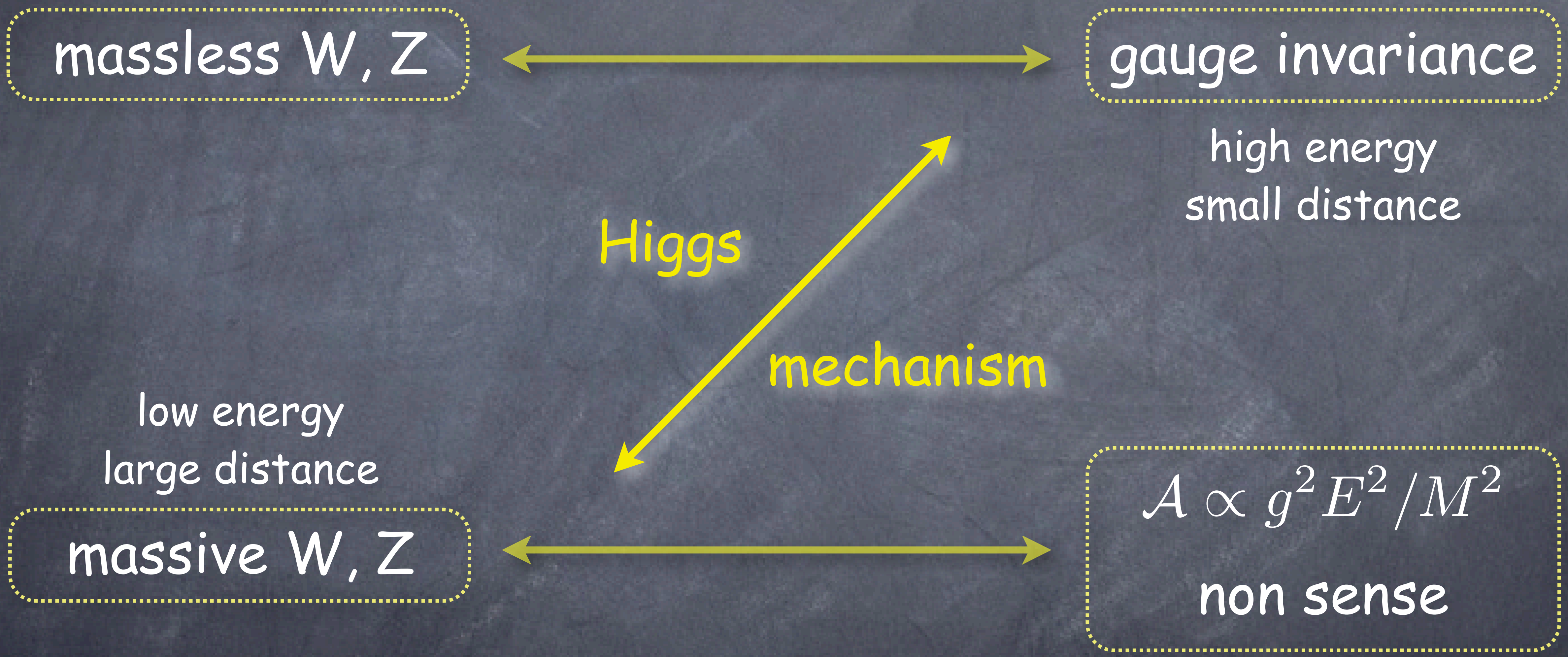
$$\mathcal{A} = g^2 \left(\frac{M_H}{2M_W} \right)^2$$

The Higgs boson unitarize the W scattering
(if its mass is below ~ 700 GeV)

Lewellyn Smith '73
Dicus, Mathur '73
Cornwall, Levin, Tiktopoulos '73

W_L scattering = pion scattering
Goldstone equivalence theorem

Higgs as UV moderator



massless W, Z

gauge invariance

high energy
small distance

Higgs

mechanism

low energy
large distance

massive W, Z

$A \propto g^2 E^2 / M^2$

non sense

Higgs Mechanism: a model without dynamics

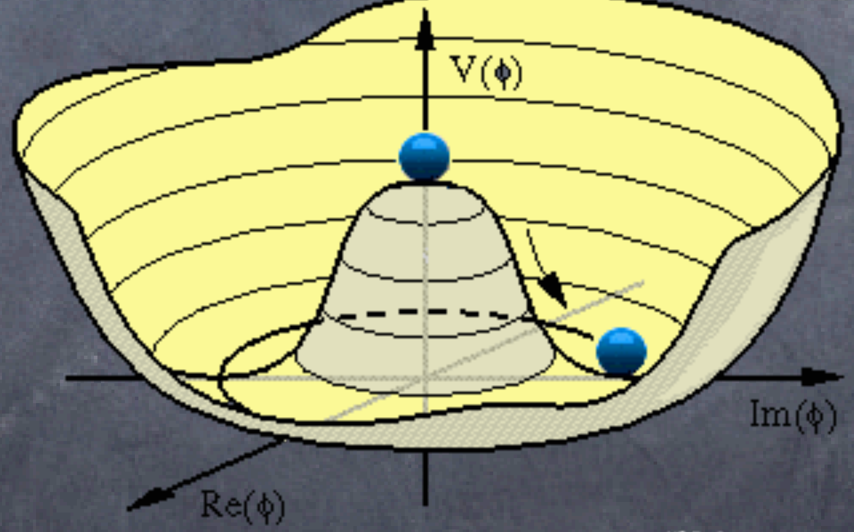
Why is EW symmetry broken ?

Because μ^2 is negative

Why is μ^2 negative ?

Because otherwise, EW symmetry won't be broken

$$V(h) = \frac{1}{2}\mu^2 h^2 + \frac{1}{4}\lambda h^4$$



The Higgs mechanism is a description of EWSB. It is not an explanation. No dynamics to explain the instability at the origin.

Physics Beyond the Higgs?

Is the Standard Model with a Higgs a UV finite theory?
i.e. valid to arbitrarily high energies

Of course, the SM will fail around the Planck scale
but the real question is

Is there any reason to think there is new physics
between the weak scale and the Planck scale?

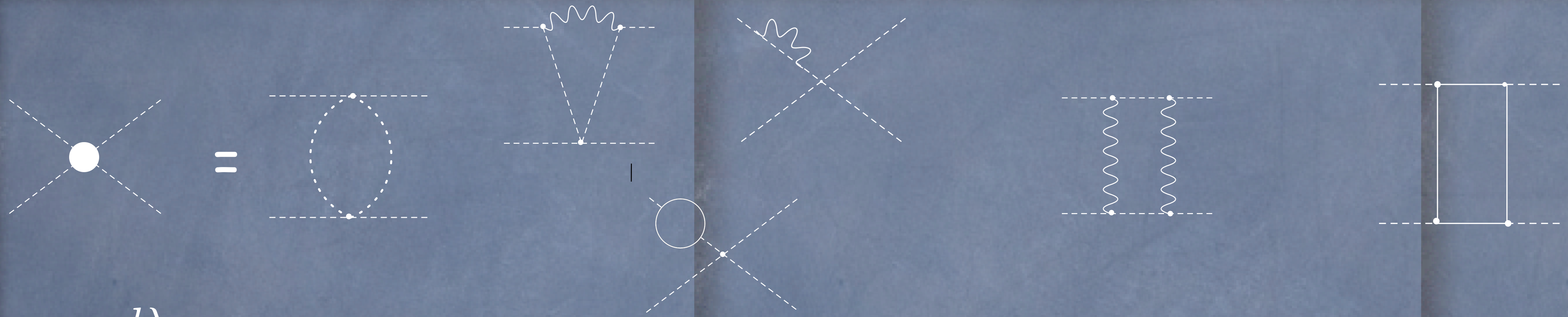
Quantum corrections of the Higgs potential

Quantum Behavior of the Higgs^4 Coupling (I)

$$V(h) = -\tfrac{1}{2}\mu^2 h^2 + \tfrac{1}{4}\lambda h^4$$

$vev: v^2 = \mu^2/\lambda$

$\mathrm{mass}\ : m_H^2 = 2\lambda v^2$



$$16\pi^2 \frac{d\lambda}{d\ln Q} = 24\lambda^2 - (3g'^2 + 9g^2 - 12y_t^2)\lambda + \tfrac{3}{8}g'^4 + \tfrac{3}{4}g'^2 g^2 + \tfrac{9}{8}g^4 - 6y_t^4 +$$

Higher loops
Small Yukawa

Large mass (λ dominated RGE)

$$16\pi^2 \frac{d\lambda}{d\ln Q} = 24\lambda^2$$

λ increases with Q: IR-free coupling

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

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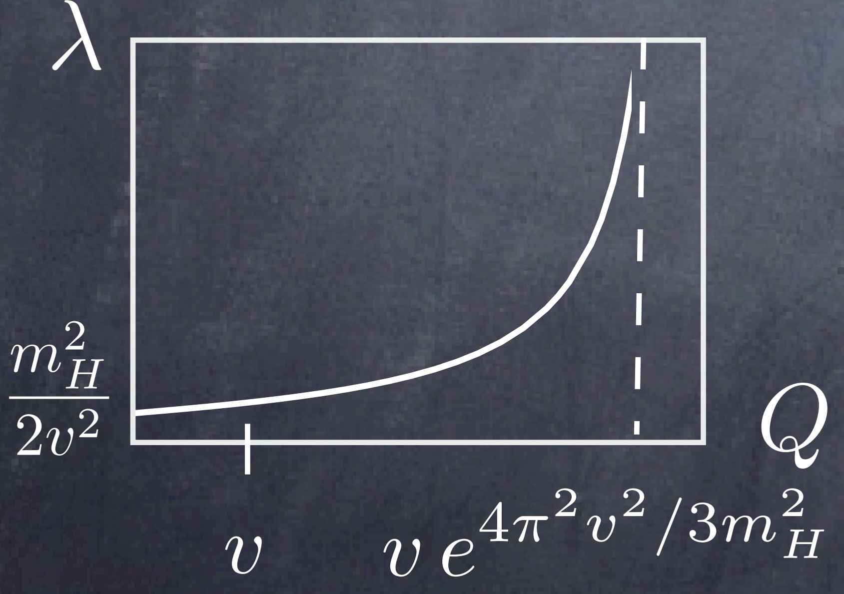

Landau pole

$$\Lambda \leq v\, e^{4\pi^2 v^2/3m_H^2}$$

New physics should appear before that point to restore stability

for m_H fixed, upper bound on Λ
for Λ fixed, upper bound on m_H

No microscopic description: for $\Lambda \to \infty$, trivial theory (λ=0)

Quantum Behavior of the Higgs^4 Coupling (II)

$$16\pi^2 \frac{d\lambda}{d\ln Q} = 24\lambda^2 - (3g'^2 + 9g^2 - 12y_t^2)\lambda + \tfrac{3}{8}g'^4 + \tfrac{3}{4}g'^2 g^2 + \tfrac{9}{8}g^4 - 6y_t^4 + $$ Higher loops Small Yukawa

Small mass (y_t dominated RGE)

$$16\pi^2 \frac{d\lambda}{d\ln Q} = -6y_t^4$$

λ decreases with Q.

$$\left(16\pi^2 \frac{dy_t}{d\ln Q} = \frac{9}{2}\, y_t^3 + \text{Higher loops Small Yukawa} \qquad y^2(Q) = \frac{y^2(Q_0)}{1 - \frac{9}{16\pi^2} y^2(Q_0) \ln \frac{Q}{Q_0}} \right)$$

$$\boxed{\lambda(Q) = \lambda_0 - \frac{\frac{3}{8\pi^2} y_0^4 \ln \frac{Q}{Q_0}}{1 - \frac{9}{16\pi^2} y_0^2 \ln \frac{Q}{Q_0}}}$$

$2\pi^2 m_H^2/3y_t^4 v^2$

Quantum Behavior of the Higgs^4 Coupling (II)

$$16\pi^2 \frac{d\lambda}{d\ln Q} = 24\lambda^2 - (3g'^2 + 9g^2 - 12y_t^2)\lambda + \tfrac{3}{8}g'^4 + \tfrac{3}{4}g'^2 g^2 + \tfrac{9}{8}g^4 - 6y_t^4 +$$ Higher loops Small Yukawa

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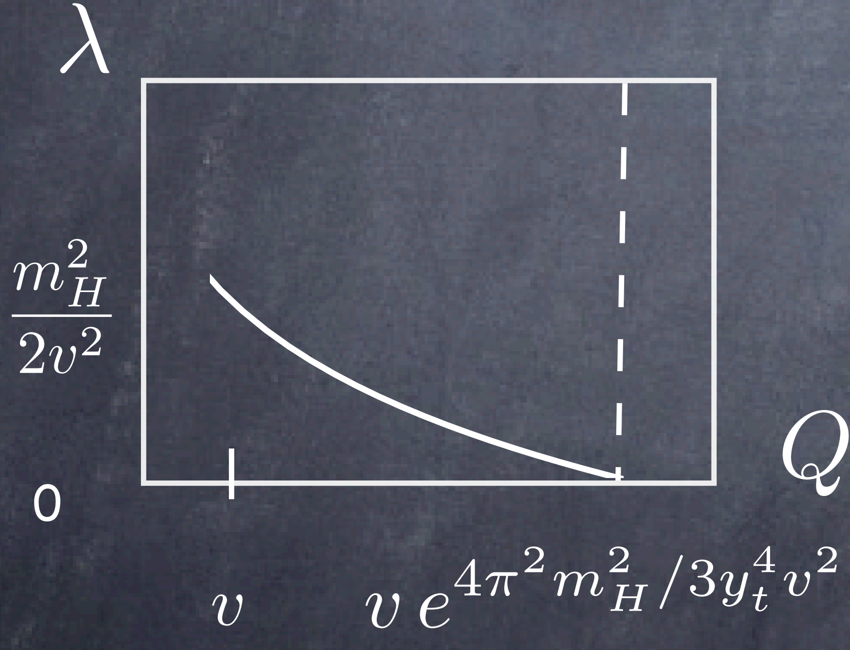


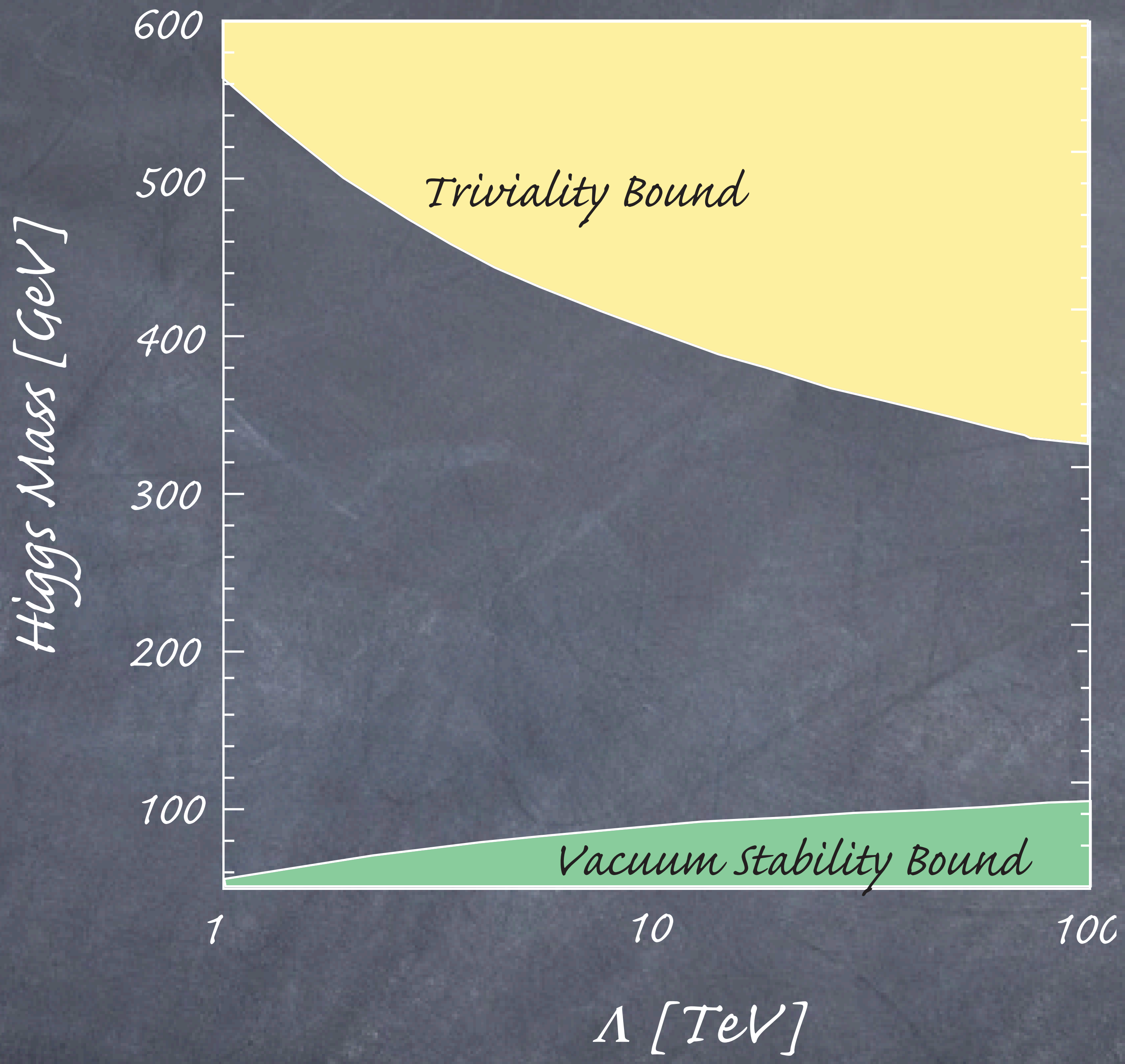
$\lambda < 0$ ⇛ potential unbounded from below

$\lambda(Q) = 0$ for $\lambda_0 \approx \frac{3}{8\pi^2} y_0^4 \ln\frac{Q}{Q_0}$

New physics should appear before that point to restore stability

$$\Lambda \le v\, e^{4\pi^2 m_H^2/3y_t^4 v^2}$$

for Λ fixed, lower bound on m_H



the SM is not UV complete

it is an effective theory of a more comprehensive theory

the cutoff of the SM can be rather low

Solution to the Higgs^4 Coupling Instabilities

find a symmetry such that

$$\boxed{\lambda \equiv g^2}$$

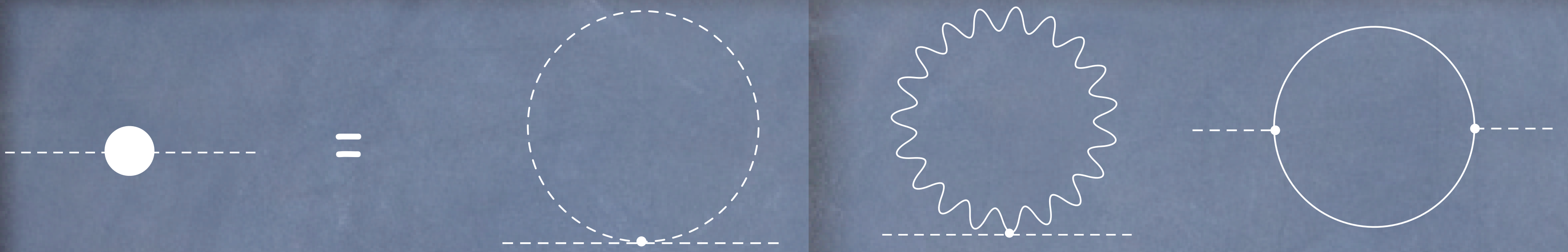
the Higgs quartic will inherit the good UV asymptotically free behavior of the gauge coupling

Examples of such symmetry:

- supersymmetry
- gauge-Higgs unification: the Higgs is identified as a component of the gauge field along some extra-dimensions.

Quantum Instability of the Higgs Mass

so far we looked only at the RG evolution of the Higgs quartic coupling (dimensionless parameter). The Higgs mass has a totally different behavior: it is higly dependent on the UV physics, which leads to the so called hierarchy problem



+ Higher loops
Smaller Yukawa

$$\int \frac{d^4k}{(2\pi)^4}\frac{1}{k^2-m^2} \propto \Lambda^2 \qquad \int \frac{d^4k}{(2\pi)^4}\frac{k^2}{(k^2-m^2)^2} \propto \Lambda^2$$

$$m_H^2 \sim m_0^2 - (115\ \text{GeV})^2 \left(\frac{\Lambda}{400\ \text{GeV}}\right)^2$$

A low-mass Higgs boson is imperiled by quantum corrections.

Must add a symmetry such that, until this symmetry is broken,
a Higgs mass is forbidden

Symmetries for a natural EWSB

How to Stabilize the Higgs Potential

Goldstone's Theorem

spontaneously broken global symmetry ⇨ massless scalar

... but the Higgs has sizable non-derivative couplings

The spin trick

a particle of spin s: 2s+1 polarization states

...with the only exception of a particle moving at the speed of light

... fewer polarization states

Spin 1 Gauge invariance ⟶ no longitudinal polarization ↘ m=0

Spin 1/2 Chiral symmetry ⟶ only one helicity ↗ m=0

... but the Higgs is a spin 0 particle

Symmetries to Stabilize a Scalar Potential

Supersymmetry

fermion ~ boson

Higher Dimensional Lorentz invariance

⇚ gauge-Higgs unification models

[Manton '79, Fairlie '79, Hosotani '83 +...]

$$A_\mu \sim A_5$$

4D spin 1

4D spin 0

These symmetries cannot be exact symmetry of the Nature. They have to be broken. We want to look for a soft breaking in order to preserve the stabilization of the weak scale.

Other symmetries?

Ghost symmetry

[Grinstein, O'Connell, Wise '07]

SM particle ~ ghost

It was known since Pauli-Villars that ghosts can soften the UV behavior of the propagators. But they are unstable per se.

Lee-Wick in the 60's proposed a trick to stabilize the ghosts (at the price of of a violation of causality at the microscopic scale).

New physics and EW precision tests

New Particles & EW Precision Measurements

We've seen that we need new particles to stabilize the weak scale.
They have to be massive to evade direct searches.
They still influence SM physics and can be constrained by EW precision measurements.

Example: Take an extra heavy B' gauge boson

$$\begin{aligned}\mathcal{L} &= \tfrac{1}{2}W_3(p^2-M_W^2)W_3 + t_0 M_W^2 W_3 B + \tfrac{1}{2}B(p^2-t_0^2M_W^2)B + gJ_3W_3 + g'J_yB \\ &\quad +\tfrac{1}{2}B'(p^2-M^2)B' + g'J_yB'\end{aligned}$$

$$t_0 = g'/g$$

Define $B_{in} = B + B'$, $B_{out} = B - B'$ and integrate out B_{out}

holographic method

$$\frac{\partial\mathcal{L}}{\partial B_{out}} = 0 \Leftrightarrow B_{out} = \frac{(t_0^2M_W^2 - M^2)B_{in} - 2t_0M_W^2W_3}{2p^2 - t_0^2M_W^2 - M^2}$$

$$\begin{aligned}\mathcal{L} &= \tfrac{1}{2}W_3\left(p^2 - M_W^2 + t_0^2\frac{M_W^4}{M^2}\right)W_3 + t_0M_W^2\left(1 + \frac{p^2 - t_0^2M_W^2}{M^2}\right)W_3B_{in} \\ &\quad +\tfrac{1}{2}B_{in}\left(p^2 - t_0^2M_W^2 + \frac{p^4 - 2t_0^2M_W^2p^2 + t_0^4M_W^4}{M^2}\right)B_{in} \\ &\quad +gJ_3W_3 + g'J_yB_{in} + \mathcal{O}\left(\frac{p^6}{M^4}\right) + \mathcal{O}\left(\frac{M_W^6}{M^4}\right)\end{aligned}$$

New Particles & EW Precision Measurements

$$\mathcal{L} = \tfrac{1}{2} W_3 \left(p^2 - M_W^2 + t_0^2 \frac{M_W^4}{M^2} \right) W_3 + t_0 M_W^2 \left(1 + \frac{p^2 - t_0^2 M_W^2}{M^2} \right) W_3 B_{in}$$
$$+ \tfrac{1}{2} B_{in} \left(p^2 - t_0^2 M_W^2 + \frac{p^4 - 2 t_0^2 M_W^2 p^2 + t_0^4 M_W^4}{M^2} \right) B_{in} + g J_3 W_3 + g' J_y B_{in}$$

Mass matrix in the (W_3, B_{in}) basis

Note: det=0, so the photon is still massless!

$$\left(1 - t_0^2 \frac{M_W^2}{M^2}\right) \begin{pmatrix} M_W^2 & -t_0 M_W^2 \\ -t_0 M_W^2 & t_0^2 M_W^2 \end{pmatrix}$$

This mass matrix is diagonalized by

$$Z = c W_3 - s B_{in}$$
$$\gamma = s W_3 + c B_{in}$$

with masses

$$M_Z^2 = \frac{\left(1 - t_0^2 M_W^2 / M^2\right)}{c_0^2} M_W^2$$
$$M_\gamma^2 = 0$$

unmodified weak mixing angle $s = s_0, \quad c = c_0$

that's what you need to ensure that the photon couples to T_{3L}+Y

Rho and T parameters

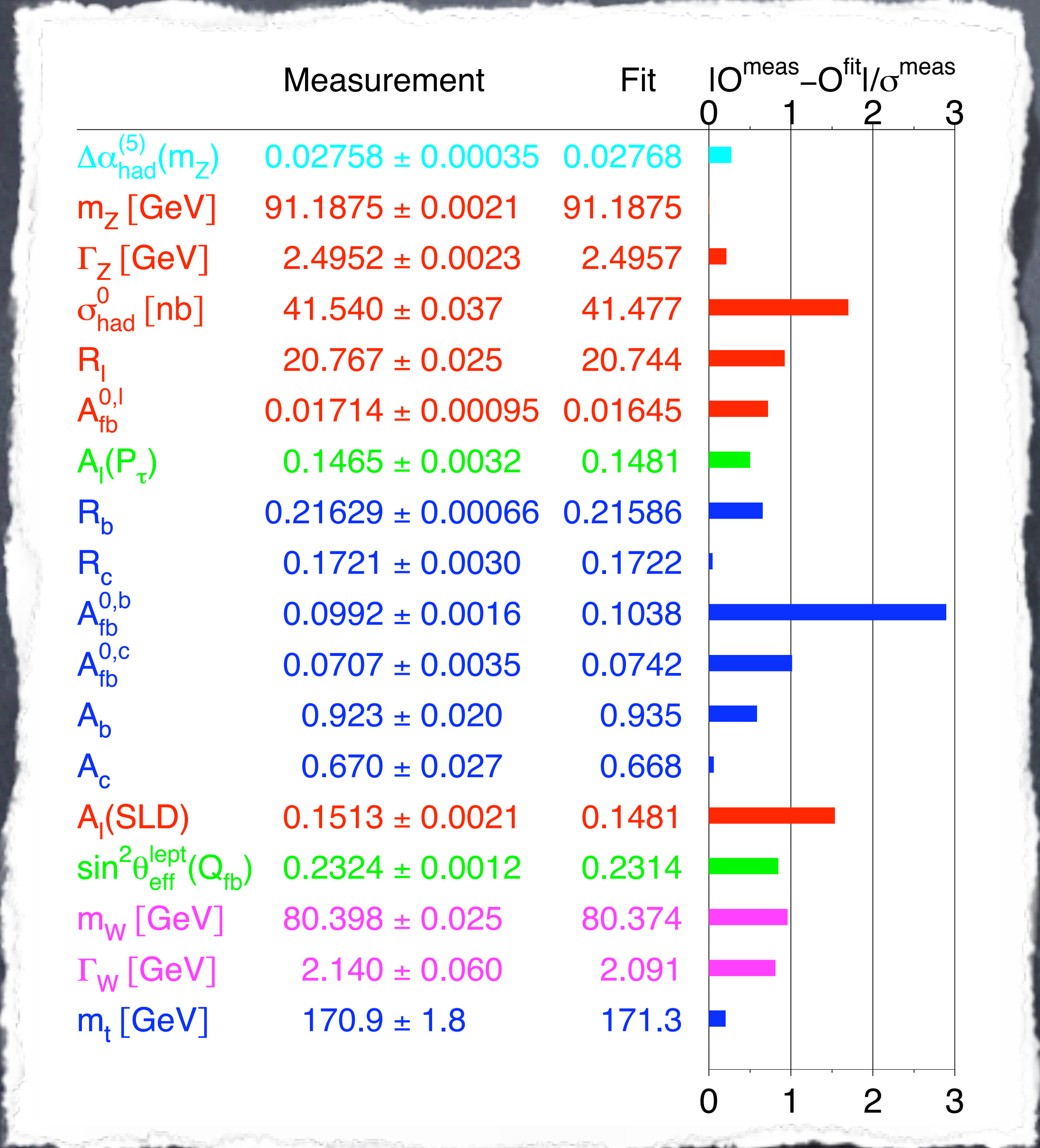
$$\rho \equiv \frac{M_W^2}{M_Z^2 c^2} \approx 1 + \frac{s_0^2}{c_0^2} \frac{M_W^2}{M^2}$$

SM deviation: $\rho \equiv 1 + \alpha_{em} T$

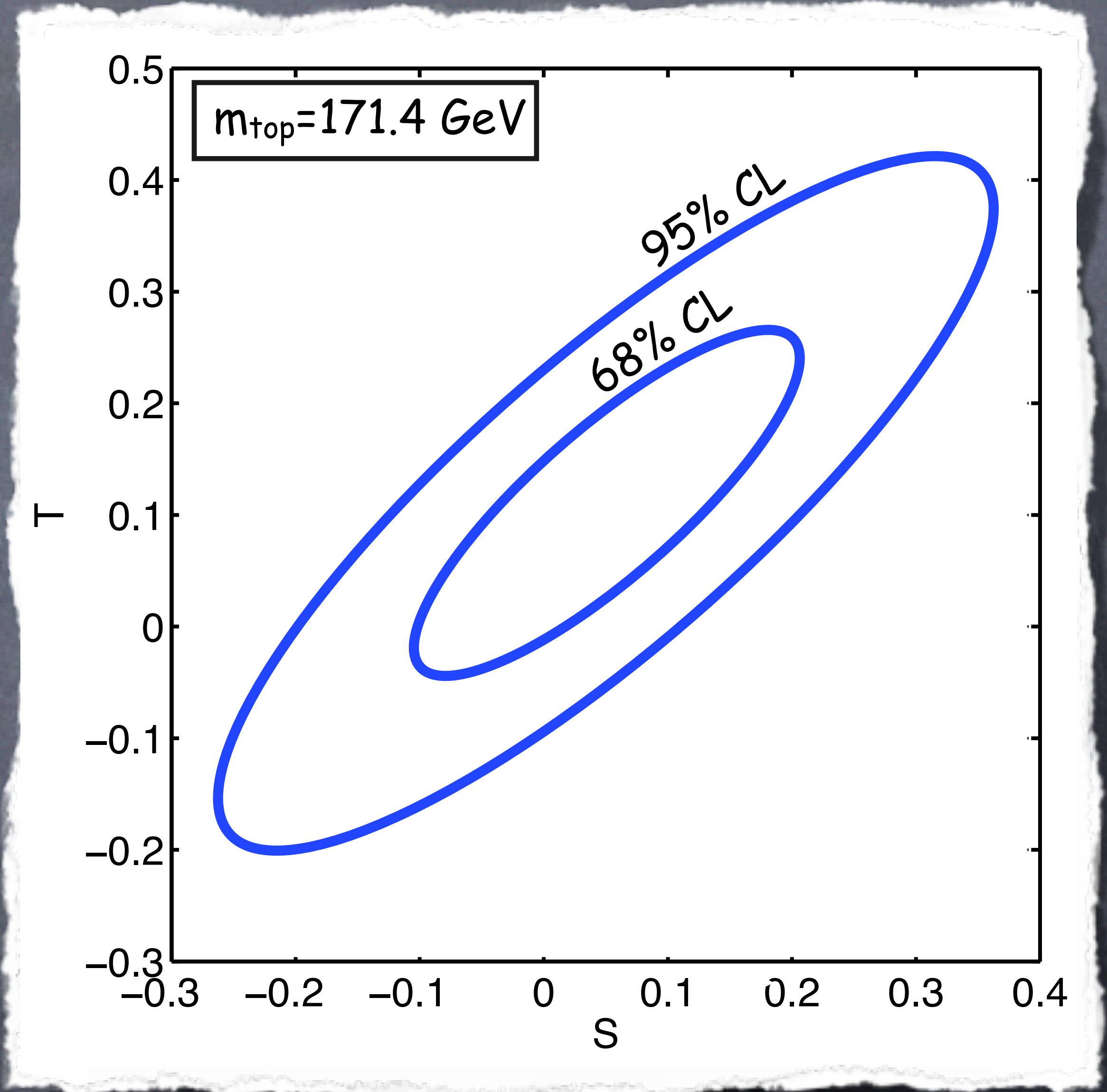
$$T = \frac{s_0^2}{\alpha_{em}\, c_0^2} \frac{M_W^2}{M^2}$$

New Physics and Oblique Corrections

In many models, the effects of new physics on EW observables can be controlled in terms of 2 parameters: S and T



	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1875
Γ_Z [GeV]	2.4952 ± 0.0023	2.4957
σ_{had}^0 [nb]	41.540 ± 0.037	41.477
R_l	20.767 ± 0.025	20.744
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21586
R_c	0.1721 ± 0.0030	0.1722
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.398 ± 0.025	80.374
Γ_W [GeV]	2.140 ± 0.060	2.091
m_t [GeV]	170.9 ± 1.8	171.3



$$\frac{c_T}{\Lambda^2}\left|H^\dagger D_\mu H\right|^2 \longleftrightarrow T = -\frac{c_T\, v^2}{2\alpha\,\Lambda^2}$$

$$\frac{c_S}{\Lambda^2}\, H^\dagger W_{\mu\nu} H B^{\mu\nu} \longleftrightarrow S = -\frac{2sc\, c_S\, v^2}{\alpha\,\Lambda^2}$$

EW Precision Measurements & Higgs Mass

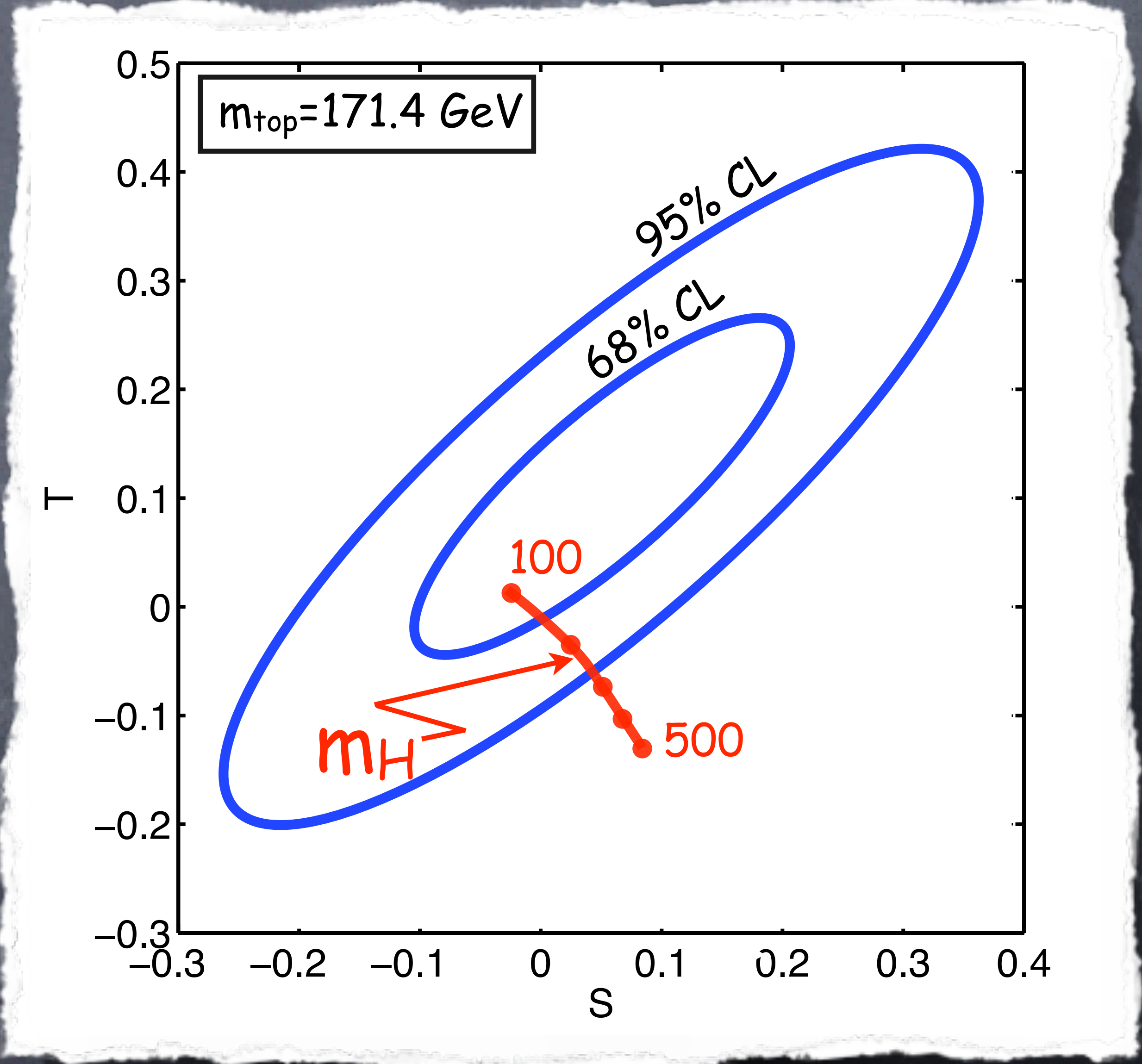
At the loop level, SM degrees of freedom contribute to S and T

$\Rrightarrow$ constraints on the Higgs mass

Higgs contribution

$$\delta S = \frac{1}{12\pi} \log \frac{m_h^2}{m_{h_0}^2}$$

$$\delta T = -\frac{3}{16\pi\, c^2} \log \frac{m_h^2}{m_{h_0}^2}$$



The Higgs cannot get too heavy
unless there exist other
(tuned) contributions to S and T

Conclusions

- Why do we expect to find a Higgs?
    1. discovery already announced to journalists and politics
    2. simplest parametrization of EWSB
    3. unitarity of WW scattering amplitude
    4. EW precision tests
- Why do we expect more than the Higgs?
    1. dark matter and matter-antimatter asymmetry → new physics not necessarily coupled to SM
    2. triviality }
    3. stability } new physics might be heavy if the Higgs is light
    4. naturality ➲ new physics has to be light if the Higgs is light

new particles/symmetries are expected to populate the TeV scale
to trigger the breaking of the EW symmetry

what is the organization principle that governs this new sector?