Particules Élémentaires, Gravitation et Cosmologie
Année 2007-'08

Le Modèle Standard et ses extensions

Higgs-less models

Particle Physics in one page

$$\mathcal{L}_{\sim SM} = -\frac{1}{4}F^{a}_{\mu\nu}F^{a\mu\nu} + i\bar{\psi}\,\not{D}\psi$$ The gauge sector (1)

$$+\psi_i\lambda_{ij}\psi_j h + h.c.$$ The flavour sector (2)

$$+|D_\mu h|^2 - V(h)$$ The EWSB sector (3)

$$+N_i M_{ij} N_j$$ The ν-mass sector (if Majorana) (4)

Can one replace line 3 with something else, without, in particular, no (relatively light) Higgs boson?

Examples of « ways out » I: Technicolour

This (pseudo?) solution is suggested by a simple observation. Consider a fake (toy) SM in which there is a single family of massless quarks and leptons and no Higgs.

Q: What is the low-energy physics of such a model?

A: Somewhat surprising. We know (2006 course) that the $SU(3)_c$ interactions break spontaneously the global symmetry $SU(2)_L \times SU(2)_R \times U(1)_V$ of m=0 QCD down to $SU(2)_V \times U(1)_V$ producing 3 massless NG bosons, the pions

$$\langle \bar{\psi}_f \, \psi_{f'} \rangle = c \, \delta_{ff'} \, \Lambda^3_{QCD}$$

The naïve answer is that the 3 pions, as well as the 3 gauge bosons of $SU(2)_L$, remain massless. This is wrong! The $SU(2)_L$ of the EW interactions is that same $SU(2)_L$ and is sp. broken

According to the general discussion of SSB of a local symmetry, the 3 pions would be "eaten up" by the 3 gauge bosons and the latter would acquire a mass.

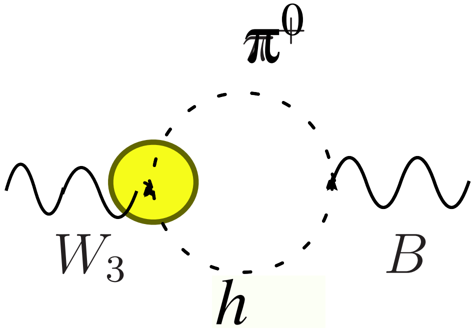
The problem (besides the disappearence of the pions) is that the W, Z masses would be on the order of Λ_{QCD}. More precisely, G_F would be of order $1/F_\pi^2 \sim (100\ \mathrm{MeV})^{-2}$ instead of the experimental value ~ $(300\ \mathrm{GeV})^{-2}$

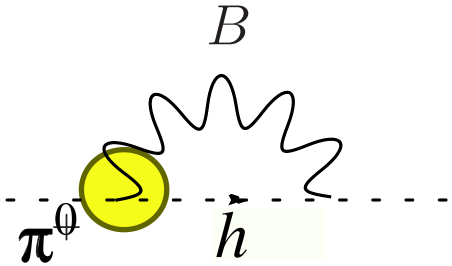
This toy model, however, suggests a better one: let's introduce, instead of the Higgs doublet, a new AF, QCD-like interaction ("technicolour") with a Λ_{tc} parameter a few thousands times larger than Λ_{QCD} and (at least) a doublet of "techniquarks"… can this work? See next week's seminar…

The virtual Higgs boson effects "seen" in the ElectroWeak Precision Tests

$$\hat{S} = \frac{g}{g'}\Pi'_{30}(0)$$

$$\hat{T} = \frac{\Pi_{33}(0) - \Pi_{WW}(0)}{m_W^2}$$

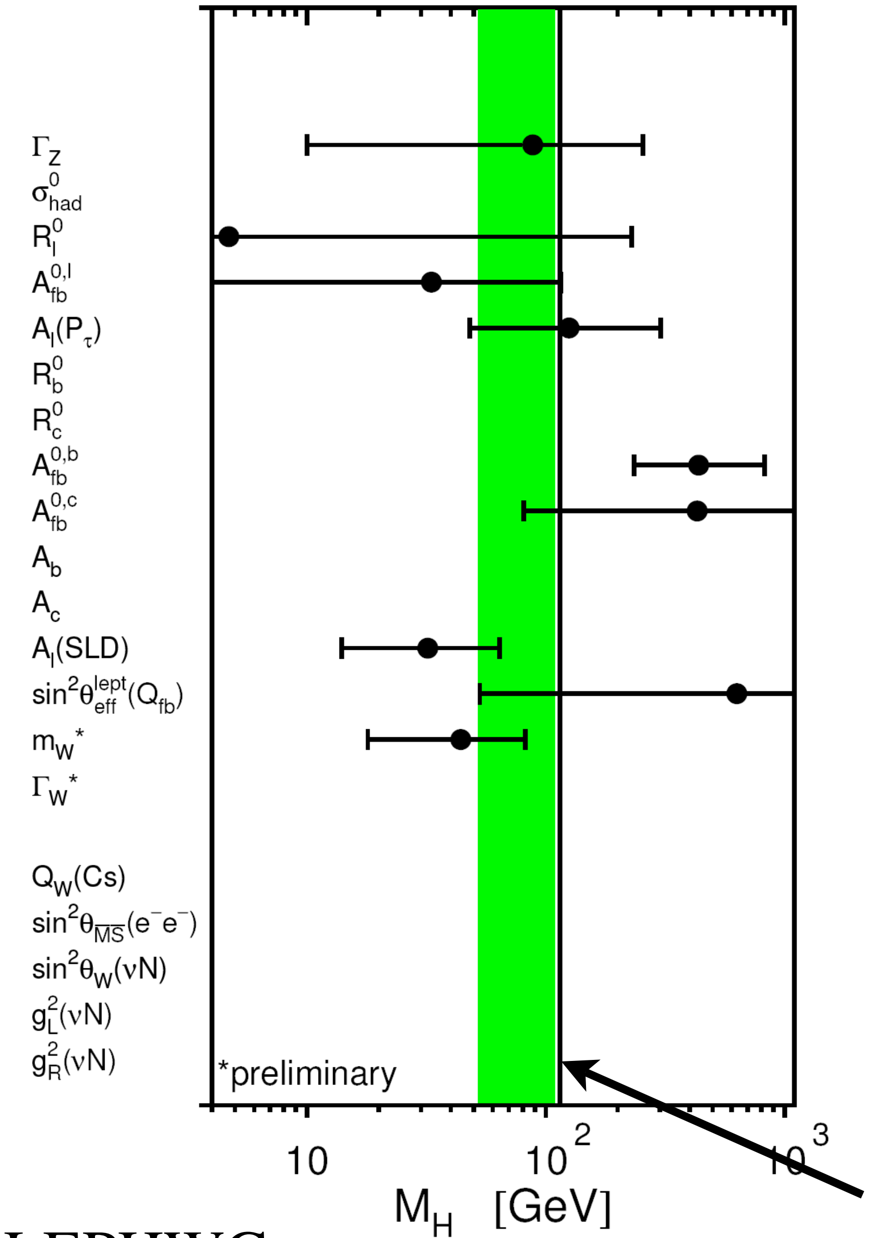




$$\hat{S} \approx \frac{G_F m_W^2}{12\sqrt{2}\pi^2}\log m_h$$

$$\hat{T} \approx -\frac{3G_F m_W^2}{4\sqrt{2}\pi^2}\tan^2\theta \log m_h$$

The Higgs boson mass in the SM



$$M_{Higgs} = (85^{+37}_{-27})\ \mathrm{GeV}/c^2$$

$$M_{Higgs} \leq 144\ \ \mathrm{GeV}/c^2\ \ 95\%\ \mathrm{CL}$$

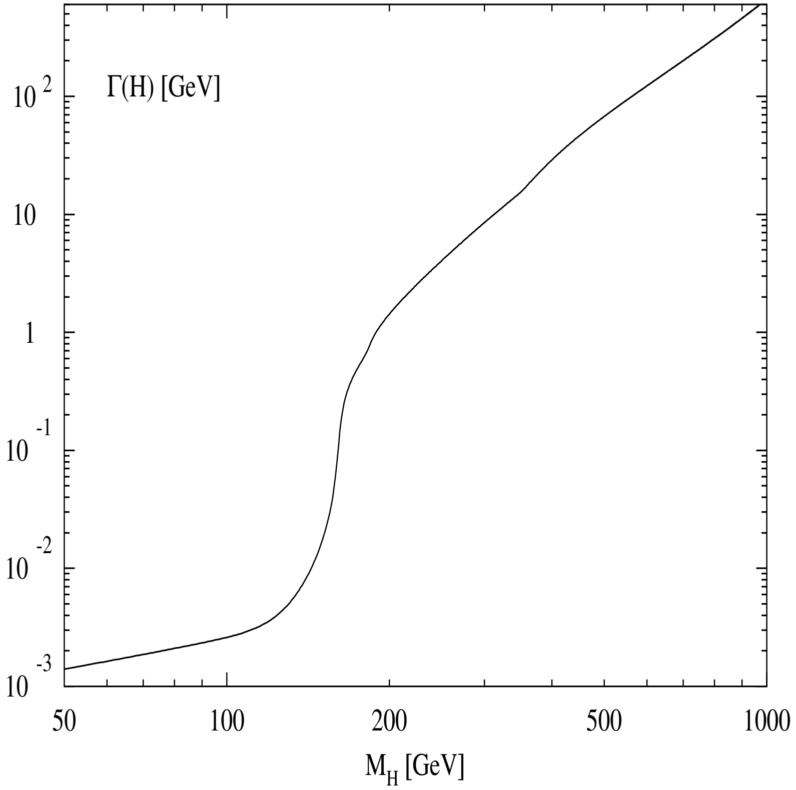
$$M_{Higgs}|_{direct} \geq 114.4 GeV$$

LEPHWG

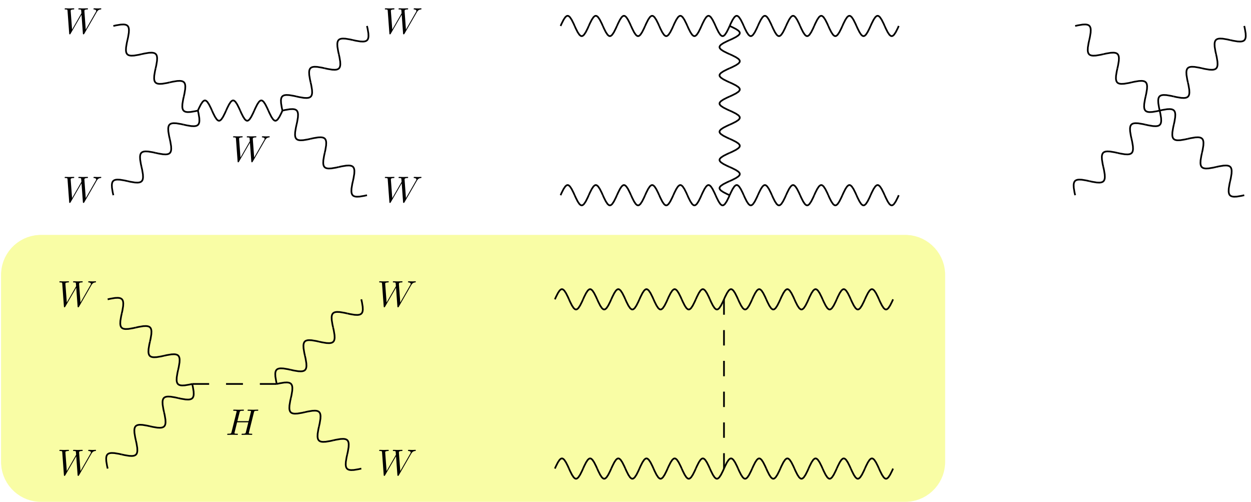
The SM as m_h gets large

$$m_h^2 = 4\lambda v^2$$

The Higgs boson ceases to be a meaningful particle as $m_h \approx 1\ TeV$

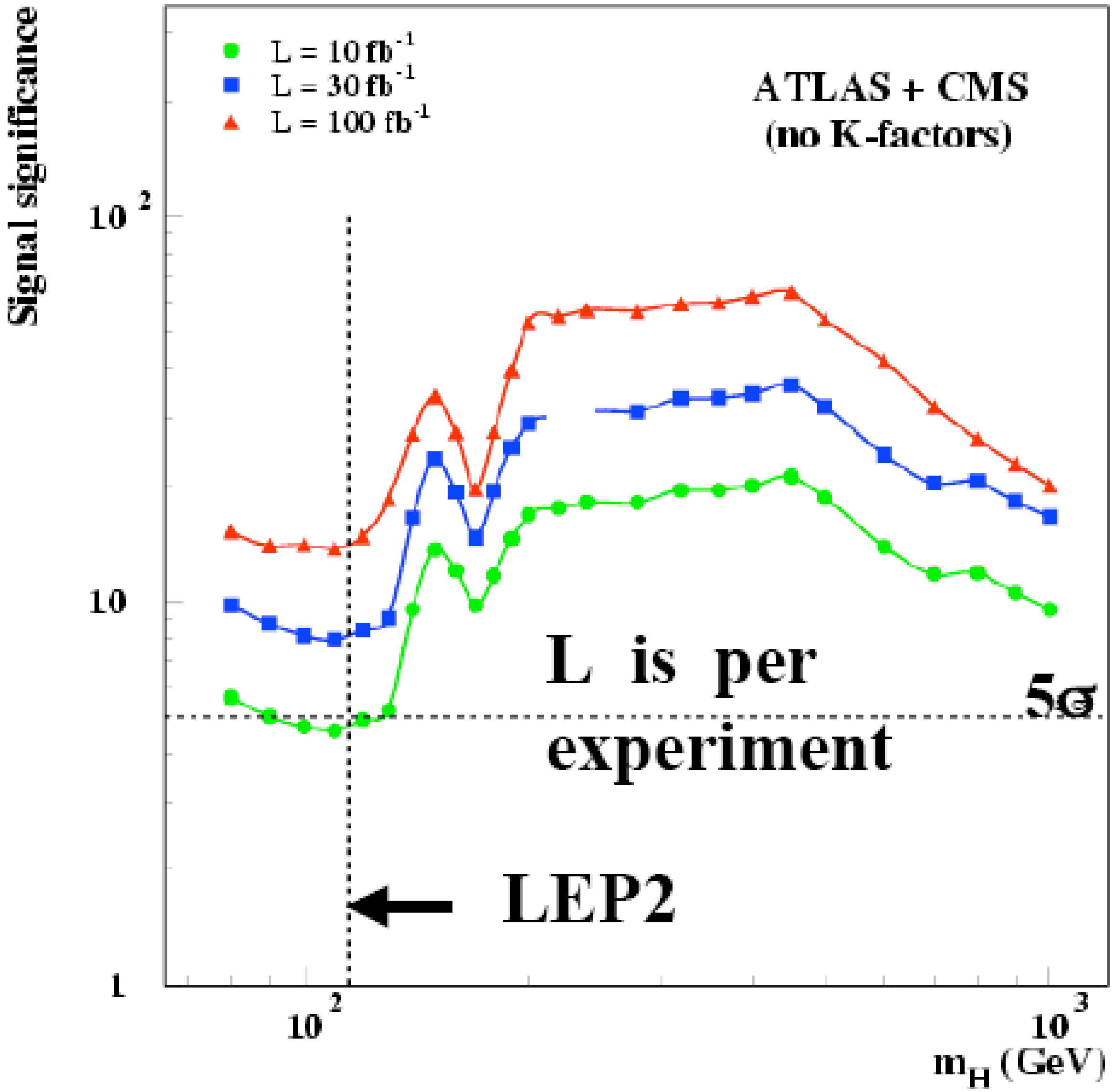


What about VV scattering?
V=W,Z



An (important) parenthetic remark

If the Higgs boson is as expected,
with a mass below a TeV, it will be found
at the LHC



$$N_X = \mathbf{L}\,\sigma(p \to X)$$

One month at design luminosity enough to explore the entire range

Study WW scattering (with longitudinal pol.s)

$$A(W^+W^- \to W^+W^-) \approx \frac{1}{v^2}[s + t - \frac{s^2}{s - m_h^2} - \frac{t^2}{t - m_h^2}]$$

$$s = E^2$$
$$t = -E^2/2(1 - z)$$
$$u = -E^2/2(1 + z)$$

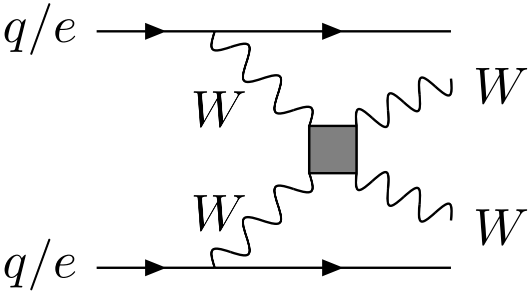
so that, for $m_h >> E$

$$A \approx \frac{s + t}{v^2}$$

Perturbation theory lost at $\sqrt{s} \approx 1.2\ TeV$

unlike what happens if $E >> m_h$ where $A \approx \frac{2m_h^2}{v^2}$

Experimentally, the central process then becomes



if we only knew something about it

A gauge invariant Higgs-less SM

In the SM: $H_{SM} = \Sigma \begin{pmatrix} 0 \\ v+h \end{pmatrix}$ $\Sigma = \exp i \frac{\pi \cdot \tau}{v}$

invariant under

$H_{SM} \Rightarrow U_L H_{SM}$ $U_L = \exp i\omega_L \cdot \tau/2$ $H_{SM} \Rightarrow \exp(i\omega_Y/2) H_{SM}$

Changing notation:

$\boxed{\Phi \equiv (v+h)\Sigma}$ $\Phi \Rightarrow U_L \Phi$ $\Phi \Rightarrow \Phi \exp(-i\omega_Y \tau_3/2)$

$$D_\mu \Phi \equiv d_\mu \Phi - g\hat{W}_\mu \Phi + g' \Phi \hat{B}_\mu \quad \hat{W}_\mu \equiv -i/2\mathbf{W}_\mu \cdot \tau \quad \hat{B}_\mu \equiv -i/2B_\mu \cdot \tau_3$$

$$H^+_{SM} H_{SM} = \frac{1}{2} Tr(\Phi^+ \Phi) \qquad |D_\mu H_{SM}|^2 = \frac{1}{2} Tr(D_\mu \Phi)^+ (D_\mu \Phi)$$

⇒ Throw away h and even forget the doublet origin of Σ

⇒ *The "ElectroWeak Chiral Lagrangian"*

The EW chiral Lagrangian

$$\mathcal{L}_{EWCh} = \mathcal{L}_G + \mathcal{L}_Y + \mathcal{L}_{NL} + \Sigma_{i=0}^{10} \mathcal{L}_i$$

$$\mathcal{L}_G = \frac{1}{4} Tr[\hat{W}_{\mu\nu} \hat{W}_{\mu\nu} + \hat{B}_{\mu\nu} \hat{B}_{\mu\nu}] + i\bar{\psi} D\psi$$

The gauge sector (1)

$$\mathcal{L}_Y = \lambda_1^{ij} \bar{Q}_L^i \Sigma Q_R^j + \lambda_2^{ij} \bar{Q}_L^i \Sigma \tau_3 Q_R^j + h.c.$$

The flavour sector (2)

$$\mathcal{L}_{NL} = \frac{v^2}{4} Tr[(D_\mu \Sigma)^+ D_\mu \Sigma]$$

The EWSB sector (3)

$$\Sigma_{i=0}^{10} \mathcal{L}_i$$

Higher derivative terms
(the price of non-renormalizability)

(By expanding the exponent in $\Sigma = \exp i \frac{\pi \cdot \tau}{v}$
one finds the W and Z masses)

In the $g', \ \lambda_2 \rightarrow 0$ limit

$SU(2)_L x SU(2)_R$ $\Sigma \Rightarrow U_L \Sigma U_R^+$

A nearby strong interaction, once again

$$A(W_LW_L) \approx \quad (E/v)^2 \quad - \quad (E/v)^2 \approx E^0$$

Gauge Higgs

Without a Higgs, perturbation theory saturated at $E \approx 4\pi v$

Obvious from the point of view of $\mathcal{L}_{EWCh}$

$$\Delta\mathcal{L}_{NL} = v^2/4|(\partial_\mu + igA_\mu)e^{i\pi^a\tau^a/v}|^2$$

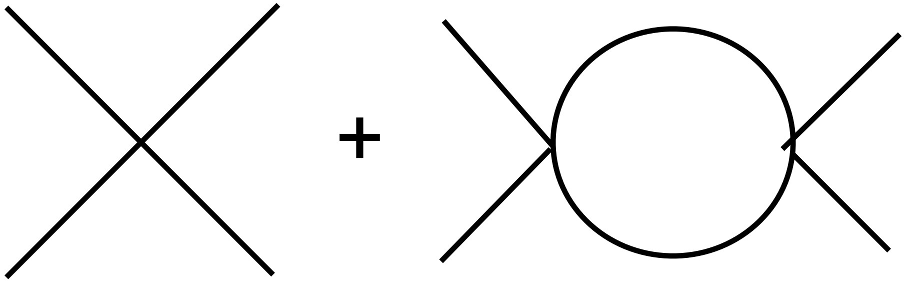
$$\approx g^2v^2A_\mu^2 + (\partial_\mu\pi)^2 + \frac{1}{v^2}\pi^2(\partial_\mu\pi)^2 + \ldots$$

$$\Rightarrow \Lambda_4 \sim 4\pi v \sim 4\pi\frac{M_W}{g}$$

Unless something happens below Λ_4

$$\approx g^2 v^2 A_\mu^2 + (\partial_\mu \pi)^2 + \frac{1}{v^2}\pi^2(\partial_\mu \pi)^2 + \ldots$$

ππ-scattering (equivalent to $W_L W_L$)



$(E/v)^2$ $\qquad$ $(E/v)^2\,(E/v)^2\frac{1}{16\pi^2}$

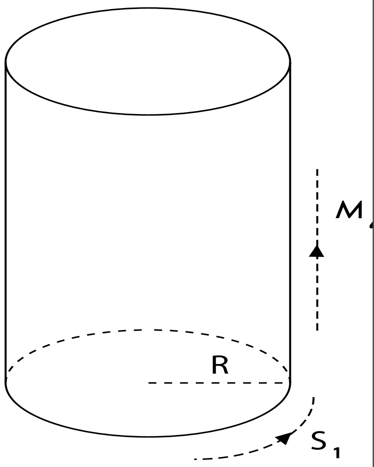
$$\Rightarrow \Lambda_4 \sim 4\pi v \sim 4\pi \frac{M_W}{g}$$

A better estimate gives $\Lambda_4 \sim \frac{4\pi v}{\sqrt{n_g}} \sim 1.2\ TeV$

We are back to the original question:
What happens in WW-scattering?

“Technicolour”? *Something else?*

A potentially interesting recent proposal



Consider a real scalar $\phi(x, x_5)$

To make contact with reality $\phi(x, x_5) = \phi(x, x_5 + 2\pi R)$

so that $\phi(x, x_5) = \sum_{n=-\infty}^{n=\infty} \phi_n(x) e^{i\frac{n x_5}{R}}$

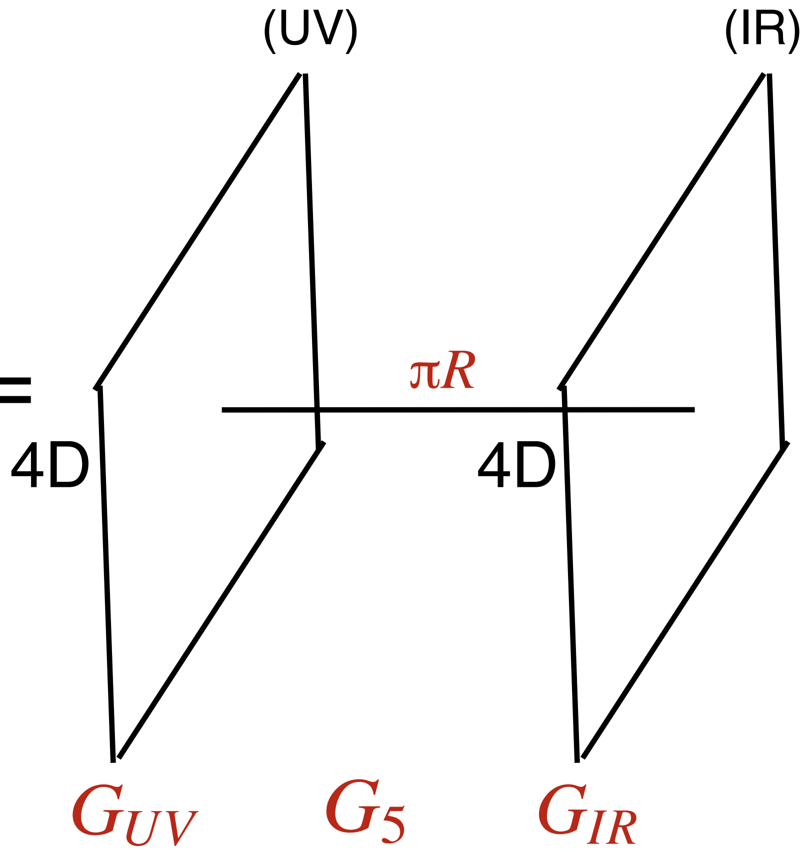
and $$\int \mathcal{L}_\phi dx^5 = -\tfrac{1}{2} \int \left[(\partial_\mu \phi)^2 - (\partial_5 \phi)^2 \right] =$$

$$\tfrac{1}{2} \int dx \sum_{-\infty}^{\infty} \left[-|\partial_\mu \phi_n|^2 + \frac{n^2}{R^2} |\phi_n|^2 \right]$$

The original 5D field decomposed into a "tower" of "Kaluza Klein" 4D fields of mass $m_n = \frac{n}{R}$

A pictorial view of space-time

Space-time
5D =



$\frac{1}{R} \simeq$ mass of the KK states

If πR is sufficiently small, we may have not seen the 5th dimension yet!

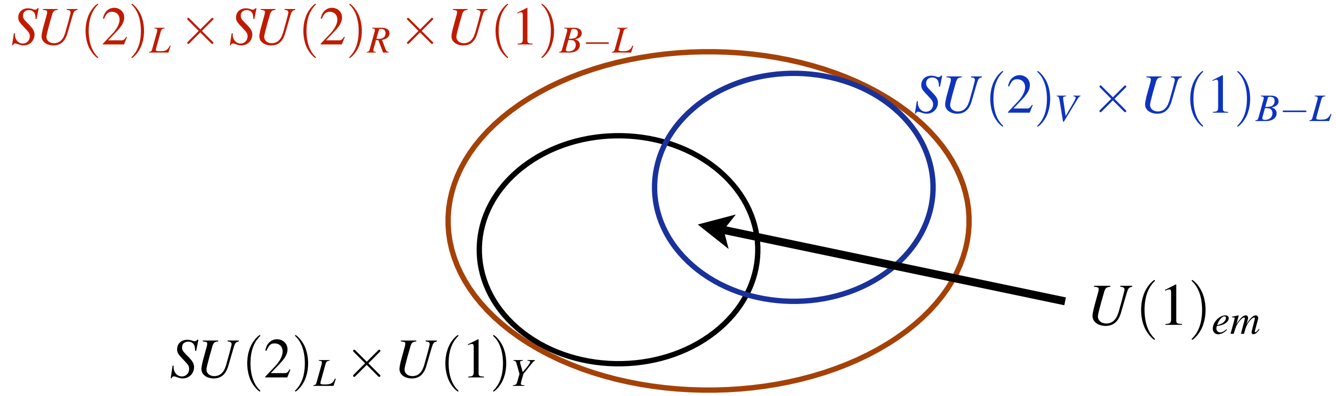
$$\pi R < 10^{-17}\ cm \approx \frac{1}{TeV}$$

Suppose now that we consider a full gauge theory in 5D

$$SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

0 πR

$SU(2)_L \times U(1)_Y$ $SU(2)_V \times U(1)_{B-L}$



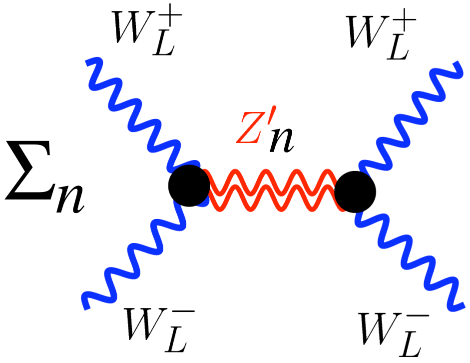
$SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

$SU(2)_V \times U(1)_{B-L}$

$U(1)_{em}$

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

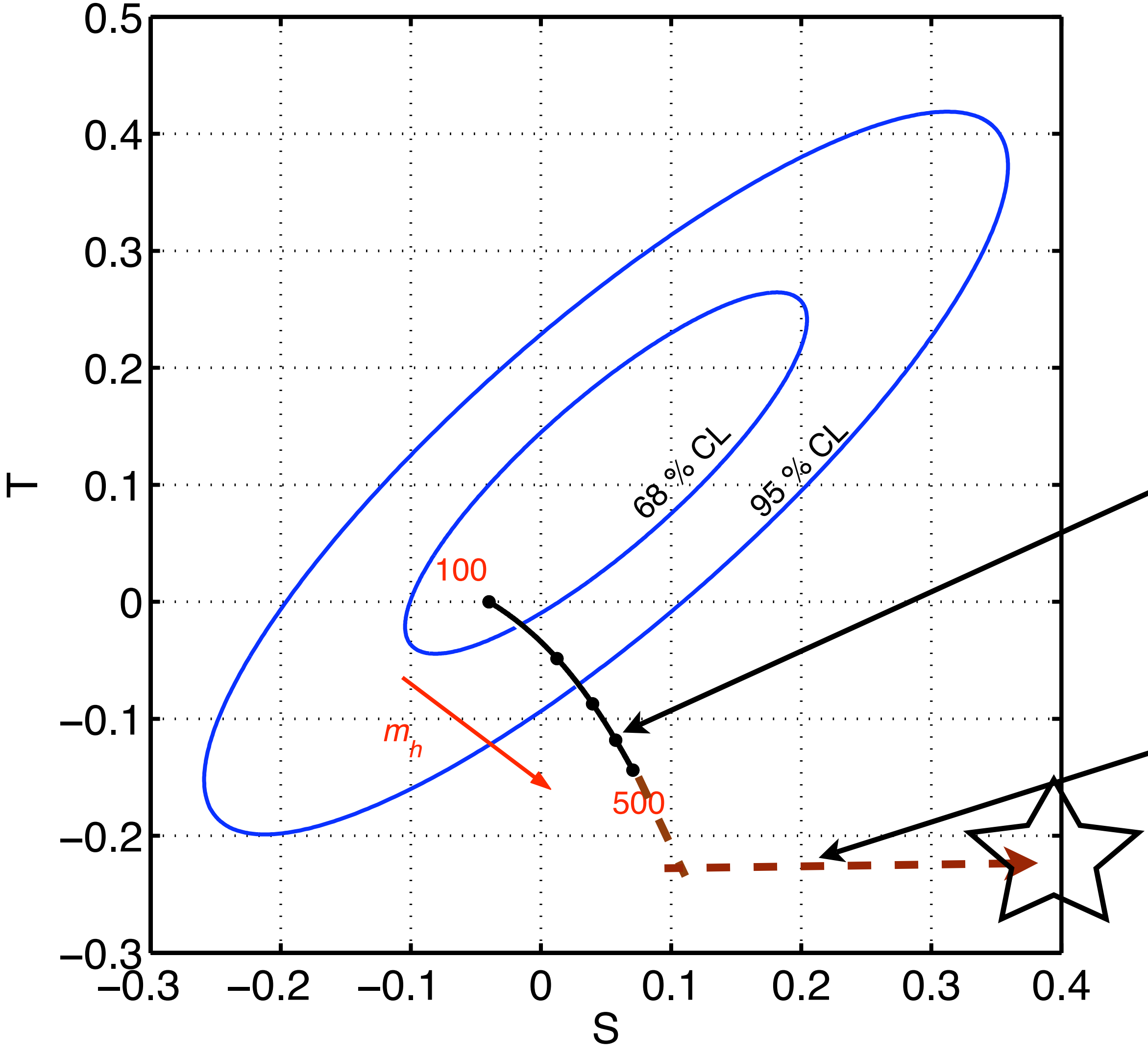
It can be shown that the exchanges of KK vector bosons in WW-scattering, can delay the onset of the strong interaction



The KK vector bosons taking the place of the Higgs boson

⇒ the particles to be looked for in place of the Higgs boson

An apparently persistent problem



a loop effect

$S,\ T|_{SM}(m_h \sim \Lambda_4)$

a tree level effect

as seemingly happening in standard Technicolour

(unless something missing:

a new indirect effect?

our inability to compute in strong interactions?)