Effects of color octet scalars on the theoretical predictions of BR($B \rightarrow X_s \gamma$) and M_W

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19 July 2010

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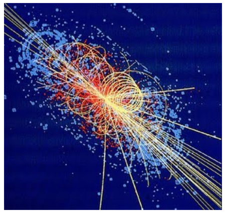
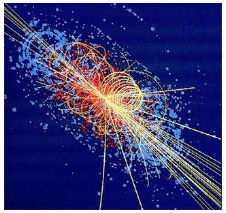


- The Standard Model of elementary particles
- Physics beyond the SM
- The Manohar-Wise model
- $B \to X_s \gamma$ decay
- Electroweak precision effects
- Conclusions

The Standard Model



The SM is a non abelian gauge theory based on the group

$SU(3)_C \times SU(2)_L \times U(1)_Y$

$SU(3)_C$ strong interactions QCD
$$\mathcal{L}_{QCD} = -\frac{1}{4}\sum_{a=1}^{8} F^{a\mu\nu}F^{a}_{\mu\nu} + \sum_{j=1}^{n_f} \bar{q}_j(i\gamma^\mu D_\mu - m_j)q_j$$

$SU(2)_L \times U(1)_Y$ electroweak interactions
$$\mathcal{L}_{EW} = \mathcal{L}_{gauge} + \mathcal{L}_{Higgs} + \mathcal{L}_{Yukawa}$$

Spontaneous symmetry breaking

Higgs mechanism

$U(1)_Q$ electromagnetic interactions QED

Masses for vector bosons and fermions + Higgs boson

The Standard Model

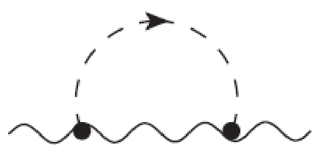
The Higgs sector has an approximate global symmetry

$$\mathcal{L}_{Higgs} = (D_\mu \phi)^\dagger (D^\mu \phi) - V(\phi, \phi^\dagger) \qquad V(\phi, \phi^\dagger) = -\mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$$

Turning off electromagnetism in the limit g'→0 there is a SU(2) custodial symmetry. Vector bosons W,Z belong to a triplet with equal masses.

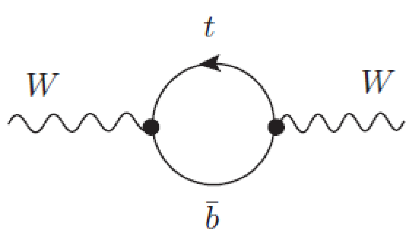
$$\rho = \frac{m_W^2}{m_Z^2 \cos^2 \theta_w} = 1$$

Custodial symmetry preserves this relation from radiative corrections.



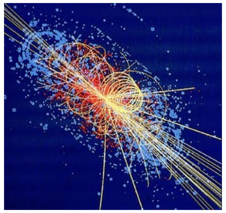
$$\rho \approx 1 - \frac{11 G_F m_Z^2 \sin^2 \theta_w}{24\sqrt{2}\pi^2} \ln \frac{m_H^2}{m_Z^2}$$

In the limit of mass-degenerate isospin partners, the same symmetry extends to Yukawa couplings.



$$\rho \approx 1 + \frac{3 G_F}{8\sqrt{2}\pi^2} \left(m_t^2 + m_b^2 - 2 \frac{m_t^2 m_b^2}{m_t^2 - m_b^2} \ln \frac{m_t^2}{m_b^2} \right)$$

The Standard Model



The SM is very predictive, up to now it has worked very well.

No signal of new physics (NP) has been found in electroweak precision tests and flavor physics.

Nevertheless there are many hints for physics beyond the SM:

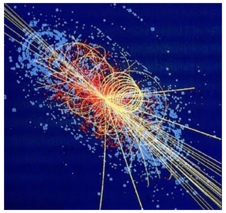
Conceptual:

- quantum gravity
- hierarchy problem
- flavor structure

Phenomenological:

- neutrino masses and mixing
- couplings unification
- dark matter/energy

Physics beyond the SM



In the SM FCNCs are naturally suppressed by the structure of couplings (GIM mechanism). The agreement with experiments is very good.

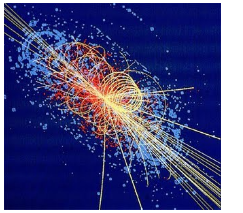
Generally speaking NP models give rise to large FCNC effects, in contrast with the experimental suppression.

There is a general scheme of model building that naturally avoids FCNC, through the principle of Minimal Flavor Violation (MFV).

Flavor conservation "follows from the group structure and representation content of the theory, and does not depend on the values taken by the parameters of the theory".

Glashow, Weinberg '77

The Manohar-Wise Model



The scalar sector with one Higgs doublet is based on a property of "minimality". Adding new scalars leads to large FCNC effects.

Which is the most general structure that *naturally* maintains the suppression of FCNCs?

$$\mathcal{L} = -y^u_{ij}\bar{u}^i_R Q^j_L H - y^d_{ij}\bar{d}^i_R Q^j_L H^\dagger + h.c.$$

Scalar representations of SU(3)xSU(2)xU(1) that couple to quarks

$$(1,2)_{1/2} \quad (8,2)_{1/2} \quad (6,3)_{1/3} \quad (6,1)_{4/3,1/3,-2/3} \quad (3,3)_{-1/3} \quad (3,1)_{2/3,-1/3,-4/3}$$

Yukawa couplings must be diagonal in the basis of quarks mass eigenstates.

Standard Model

$$M^u_{ij} = y^u_{ij}\langle H\rangle \qquad M^d_{ij} = y^d_{ij}\langle H\rangle^\dagger$$

$$M^u = \sum_\alpha y^u_\alpha \langle H_\alpha\rangle \qquad M^d = \sum_\beta y^d_\beta \langle H_\beta\rangle^\dagger$$

e.g. Glashow-Weinberg: a different doublet for every charge sector (u, d, l)

Naturalness implies MFV (Manohar-Wise) and the only possible representations are

$(1,2)_{1/2}$ Standard Higgs doublet

$(8,2)_{1/2}$ Color octet scalars

The Manohar-Wise Model

We add to SM fields a scalar multiplet $(8,2)_{1/2}$ of colored particles (no VEV).

$$S^a = \begin{pmatrix} S^{+a} \\ S^{0a} \end{pmatrix} \quad a = 1, \dots, 8 \qquad S^{0a} = \frac{S_R^{0a} + iS_I^{0a}}{\sqrt{2}}$$

The most general renormalizable scalar potential is

$$V = \frac{\lambda}{4}\left(H^{\dagger i}H_i - \frac{v^2}{2}\right)^2 + 2m_S^2 TrS^{\dagger i}S_i + \lambda_1 H^{\dagger i}H_i TrS^{\dagger j}S_j + \lambda_2 H^{\dagger i}H_j TrS^{\dagger j}S_i$$
$$+ [\lambda_3 H^{\dagger i}H^{\dagger j}TrS_iS_j + \lambda_4 H^{\dagger i}TrS^{\dagger j}S_jS_i + \lambda_5 H^{\dagger i}TrS^{\dagger j}S_iS_j + h.c.]$$
$$+ \lambda_6 TrS^{\dagger i}S_iS^{\dagger j}S_j + \lambda_7 TrS^{\dagger i}S_jS^{\dagger j}S_i + \lambda_8 TrS^{\dagger i}S_i TrS^{\dagger j}S_j$$
$$+ \lambda_9 TrS^{\dagger i}S_j TrS^{\dagger j}S_i + \lambda_{10} TrS_iS_j TrS^{\dagger i}S^{\dagger j} + \lambda_{11} TrS_iS_jS^{\dagger j}S^{\dagger i}$$

Higgs VEV

$$m_{S^\pm}^2 = m_S^2 + \lambda_1 \frac{v^2}{4}$$
$$m_{S_R^0}^2 = m_S^2 + (\lambda_1 + \lambda_2 + 2\lambda_3)\frac{v^2}{4}$$
$$m_{S_I^0}^2 = m_S^2 + (\lambda_1 + \lambda_2 - 2\lambda_3)\frac{v^2}{4}$$

Symmetric under custodial SU(2) if

$$2\lambda_3 = \lambda_2$$
$$2\lambda_6 = 2\lambda_7 = \lambda_{11}$$
$$\lambda_9 = \lambda_{10}$$

Gauge bosons-scalars interactions

$$\mathcal{L}_{kin} = (D_\mu S^a)(D^\mu S^a)^\dagger$$

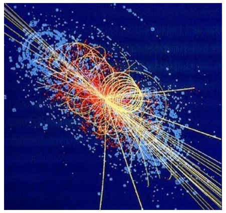
$$D_\mu S^a = \partial_\mu S^a + g_s f^{abc} G_\mu^b S^c + ig\frac{\sigma^i}{2}W_\mu^i S^a + i\frac{g'}{2}B_\mu S^a$$

SU(3) SU(2) U(1)

Fermions-scalars interactions

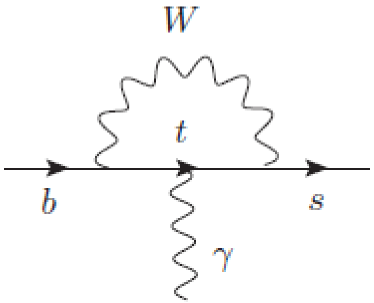
$$\mathcal{L} = -\eta_u y_{ij}^u \bar{u}_R^i T^a Q_L^j S^a - \eta_d y_{ij}^d \bar{d}_R^i T^a Q_L^j S^{a\dagger} + h.c.$$

$B \to X_s \gamma$ decay



Radiative decay of B mesons (b quark)

X_s: inclusive hadronic state with total strangeness S=-1



Rare FCNC process starting at one loop. It is very sensible to NP effects.

The experimental value and SM prediction are in good agreement. Strong constraint on flavor structure of NP models.

$$BR(B \to X_s \gamma)_{exp} = (3.52 \pm 0.32)\ 10^{-4}$$

$$BR(B \to X_s \gamma)_{SM} = (3.28 \pm 0.25)\ 10^{-4}$$

Theoretical study starts from the effective Hamiltonian

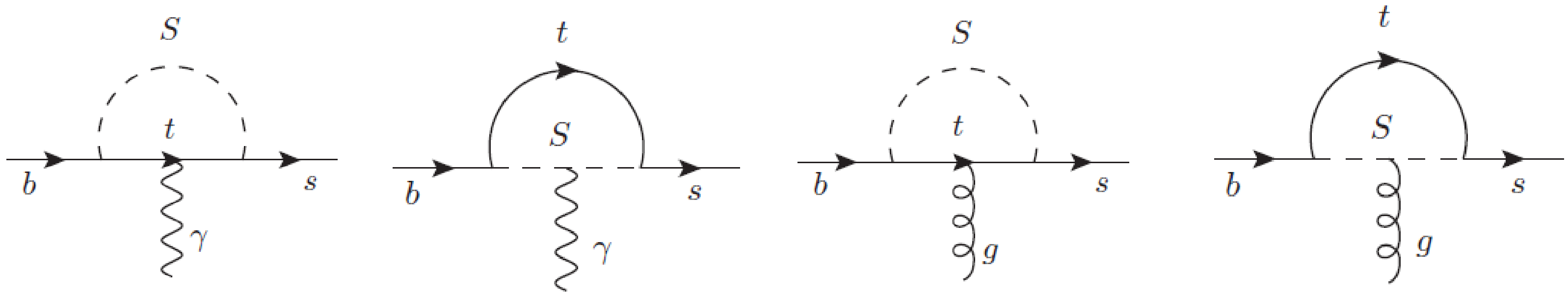
$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \sum_{i=1}^{8} C_i(\mu) Q_i(\mu)$$

$C_i(\mu)$ Wilson coefficients, high energy contributions from loops of heavy particles (effective couplings)

$Q_i(\mu)$ Non-renormalizable operators with light particles (effective vertices)

$B \to X_s \gamma$ decay

Loop exchange of color octet scalars gives new contributions to Wilson coefficients C_7 and C_8



$$C_7^{(0)MW} = |\eta_u|^2 \frac{x(-8x^3+3x^2+12x-7+6(3x-2)x\ln x)}{54(x-1)^4} + \eta_u^* \eta_d^* \frac{x(5x^2-8x+3+(4-6x)\ln x)}{9(x-1)^3}$$

$$C_8^{(0)MW} = |\eta_u|^2 \frac{x(19x^3+21x^2-51x+11+6(1-9x)x\ln x)}{144(x-1)^4} + \eta_u^* \eta_d^* \frac{x(-5x^2+2x+3+(9x-1)\ln x)}{12(x-1)^3}$$

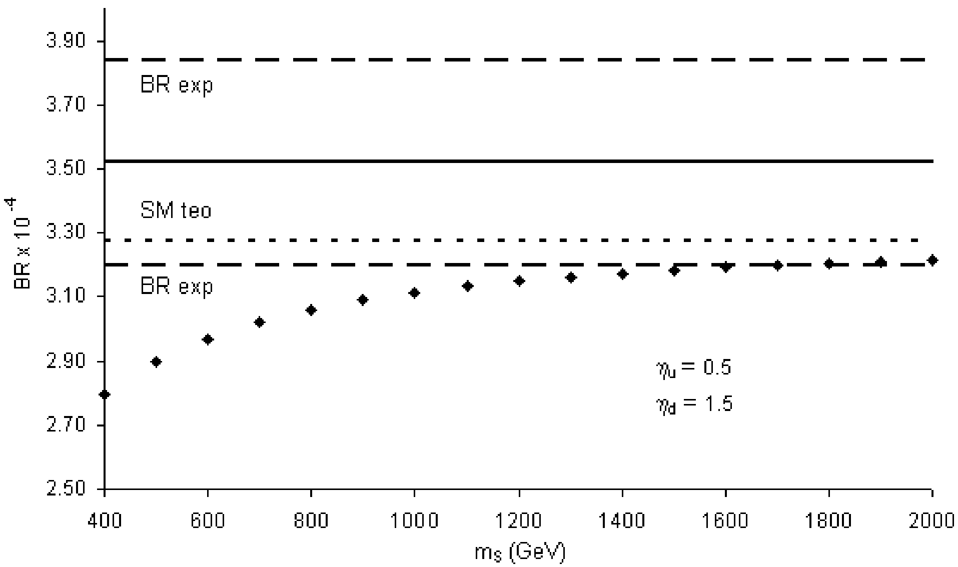
$$x = m_t^2/m_{S+}^2$$

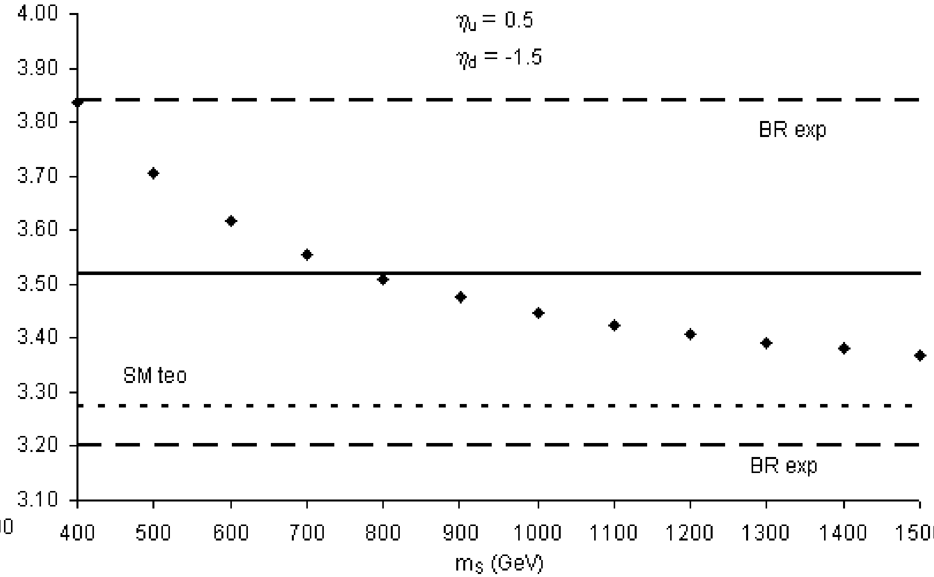
New contributions depend on the mass of charged scalar and on new couplings η_u η_d in Yukawa interactions.

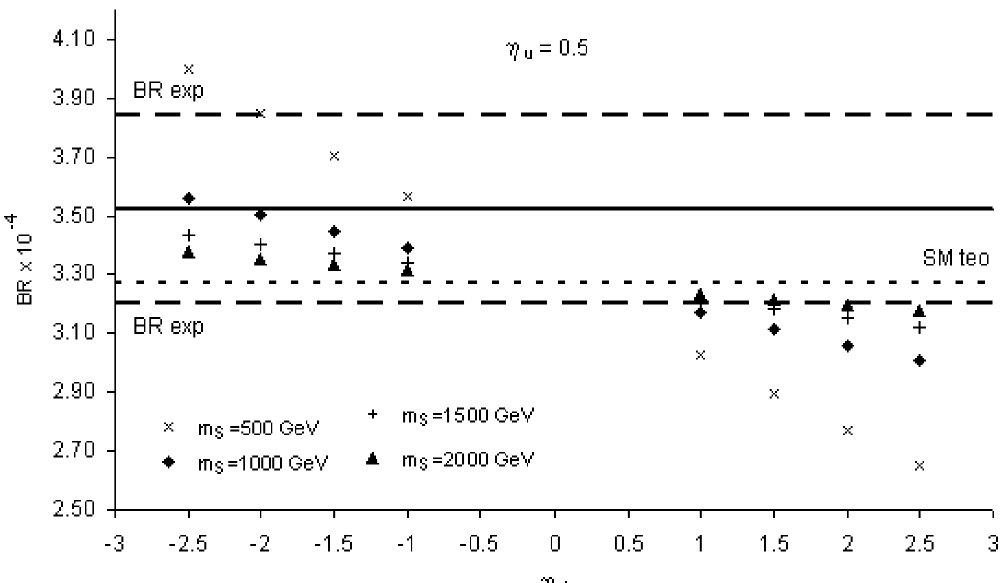
$$\mathcal{L} = -\eta_u y_{ij}^u \bar{u}_R^i T^a Q_L^j S^a - \eta_d y_{ij}^d \bar{d}_R^i T^a Q_L^j S^{a\dagger} + h.c.$$

The numerical effect on BR has been evaluated with the Fortran program SusyBSG, that evaluates the BR for the SM, THDM, MSSM.

$B \to X_s \gamma$ decay







η_u, η_d same sign:

• negative contribution, heavy scalars m_S> 1700 GeV

Opposite sign:

• positive contribution, light scalars m_S> 400 GeV

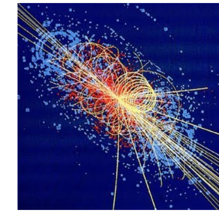
In general relevant effects:

m_S~700 GeV variation 7-8% with respect to SM

m_S~1400 GeV variation 4% with respect to SM

Raising the mass the extra contribution vanishes.

Electroweak precision effects



The study of radiative corrections is fundamental in modern precision tests of electroweak theory.

External input parameters: masses, couplings. Select the experimentally best known, e.g. α, m_Z, G_F

↓

Evaluation of radiative corrections with appropriate precision

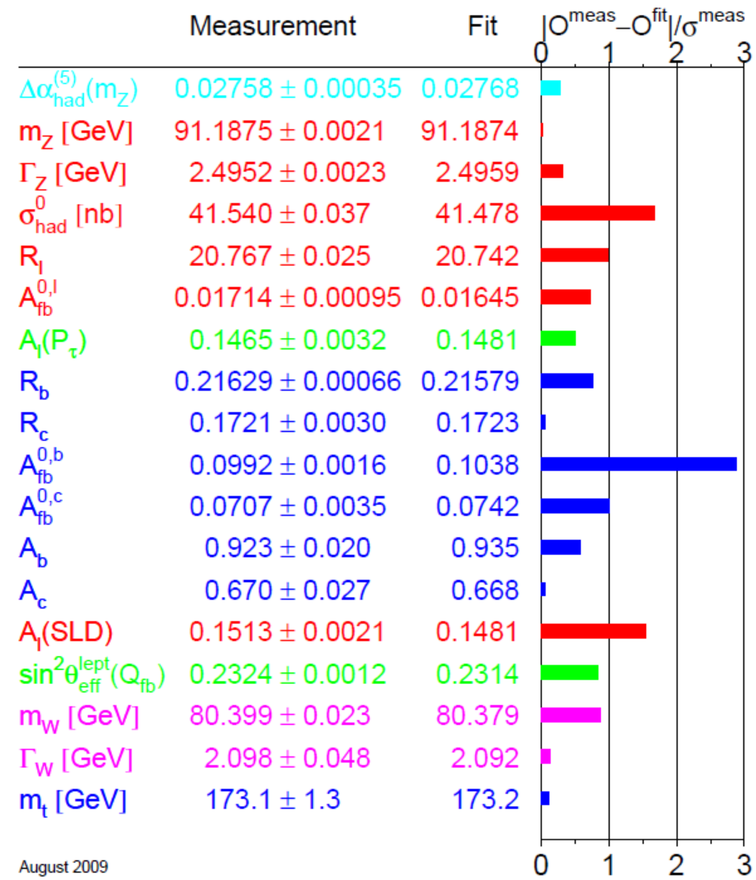
↓

Comparison with experimental measures

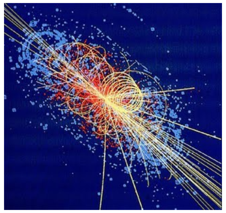
↓

Analysis of consistency of the theory, constraints on m_t, $\alpha_s(m_Z)$, m_H

Precision tests are compatible with SM, no clear signal of new physics.



Electroweak precision effects



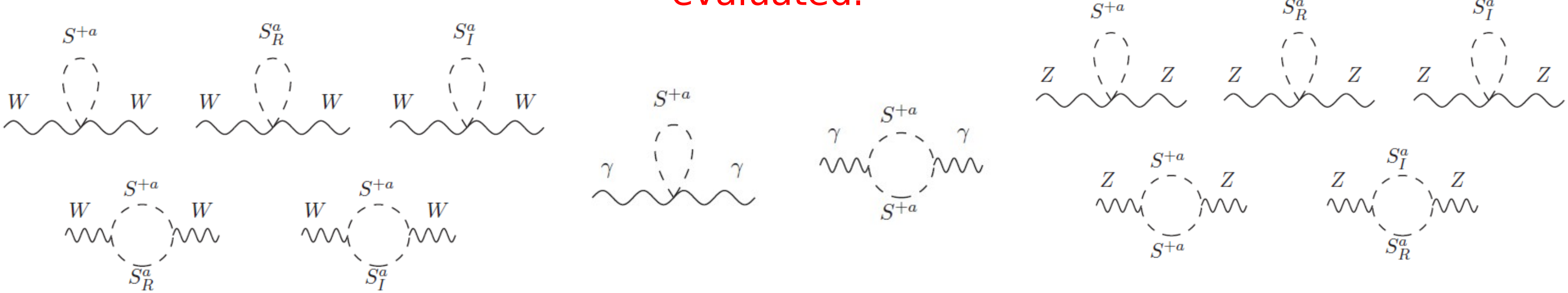
Some relations holding at tree level are modified by radiative corrections.

$$e = g\sin\theta_w \qquad \cos\theta_w = \frac{m_W}{m_Z} \qquad g' = g\tan\theta_w \qquad \frac{G_F}{\sqrt{2}} = \frac{g^2}{8m_W^2}$$

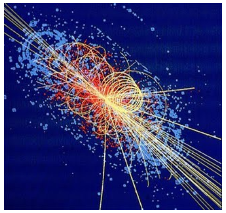
$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8m_W^2(1-\Delta r)} \qquad \sin^2\theta_w = \frac{\pi\alpha}{\sqrt{2}G_F m_W^2(1-\Delta r)} \qquad m_W^2 = \frac{m_Z^2}{2}\left(1+\sqrt{1-\frac{4\pi\alpha}{\sqrt{2}G_F m_Z^2(1-\Delta r)}}\right)$$

Δr represents the correction to the muon decay amplitude, it is evaluated from gauge bosons self-energy diagrams (universal) and from box and vertex diagrams. An other important parameter is ρ, that arises from renormalization of neutral current neutrino-hadron processes.

In this work the contributions of color octet scalars to these parameters have been evaluated.



Electroweak precision effects



From Δr we get the prediction for m_W

$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_F}\frac{1}{1-\Delta r(\alpha,m_W,m_Z,m_t,m_H)} \quad\Rightarrow\quad m_W^2=\frac{m_Z^2}{2}\left(1+\sqrt{1-\frac{4\pi\alpha}{\sqrt{2}G_F m_Z^2(1-\Delta r)}}\right)$$

current status in SM

$$\Delta r=\Delta r^{(\alpha)}+\Delta r^{(\alpha\alpha_s)}+\Delta r^{(\alpha\alpha_s^2)}+\Delta r^{(\alpha^2)}_{\rm ferm}+\Delta r^{(\alpha^2)}_{\rm bos}+\Delta r^{(G_\mu^2\alpha_s m_t^4)}+\Delta r^{(G_\mu^3 m_t^6)}$$

1 loop

$$\Delta r^{(\alpha)}=\Delta\alpha-\frac{c_w^2}{s_w^2}\Delta\rho+\Delta r_{rem}$$

We use a parameterization for numerical analysis that shows the different contributions

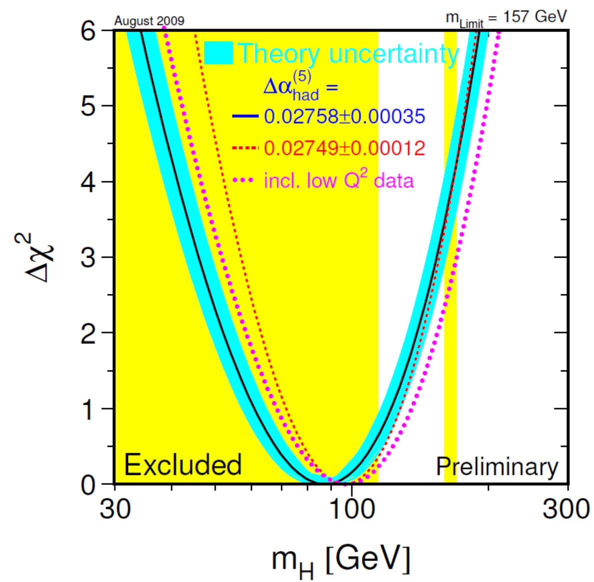
$$m_W=m_W^0\boxed{-c_1 dH-c_2 dH^2+c_3 dH^4+c_4(dh-1)}-c_5 d\alpha$$
$$+c_6 dt-c_7 dt^2-c_8 dH\,dt+c_9 dh\,dt-c_{10}d\alpha_s+c_{11}dZ$$

$$dH=\ln\frac{m_H}{100\ GeV}\qquad dh=\left(\frac{m_H}{100\ GeV}\right)^2\qquad dt=\left(\frac{m_t}{174.3\ GeV}\right)^2-1$$
$$d\alpha=\frac{\Delta\alpha}{0.05907}-1\qquad d\alpha_s=\frac{\alpha_s(m_Z)}{0.119}-1\qquad dZ=\frac{m_Z}{91.1875\ GeV}-1$$

$m_W^0=80.3799$ GeV, $c_1=0.05429$ GeV, $c_2=0.008939$ GeV
$c_3=0.0000890$ GeV, $c_4=0.000161$ GeV, $c_5=1.070$ GeV
$c_6=0.5256$ GeV, $c_7=0.0678$ GeV, $c_8=0.00179$ GeV
$c_9=0.0000659$ GeV, $c_{10}=0.0737$ GeV, $c_{11}=114.9$ GeV

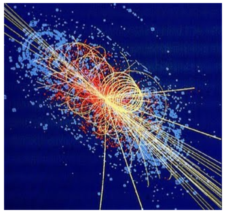
$m_H > 114.4$ GeV direct search
$m_H < 186$ GeV (95% C.L.) SM fit

$$m_H=87^{+35}_{-26}\ GeV\ (68\ C.L.)$$



Approximate the true value for m_W with an accuracy of 0.5 MeV for 10 GeV $< m_H <$ 1 TeV varying inputs in the range of 2σ.

Electroweak precision effects



$$\Delta r = \Delta r_{MS} + \Delta r_{new} \quad \Rightarrow \quad m_W = m_W^{(MS)} - \frac{A m_Z^2}{(2m_W^{(MS)2} - m_Z^2)(1-\Delta r_{MS})^2}\Delta r_{new} + O(\Delta r_{new}^2)$$

Let us assume that the parameterization gives the experimental value m_W=80.399±0.023 GeV

$$m_W = m_W^0 - c_1 dH + \ldots$$

$$m_W^0 = m_W^{0\,(old)} - C\Delta r_{new} \qquad dH = \ln m_H/100$$

m_W at l.h.s fixed to experimental value. We have two cases:

1. $\Delta r_{new} > 0$, m_W^0 decreases, to balance the effect in dH the lower limit on m_H decreases
2. $\Delta r_{new} < 0$, m_W^0 increases, to balance the effect in dH the upper limit on m_H increases

We obtain constraints on the allowed range for the Higgs mass at 1σ.

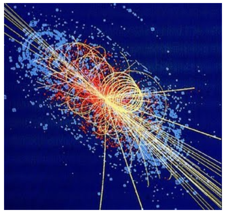
$y = c_1 dH + c_2 dH^2 - c_3 dH^4 - c_4(dh-1)$ Normally distributed around the central value with st.dev.

$$\sigma_y = \left[\sigma_{mW}^2 + \sum_i c_i^2 \sigma_i^2\right]^{\frac{1}{2}}$$

$$m_W = 80.399 \pm 0.023 \text{ GeV} \qquad m_Z = 91.1876 \pm 0.0021 \text{ GeV}$$
$$m_t = 173.1 \pm 1.3 \text{ GeV} \qquad \Delta\alpha = \Delta\alpha_{lept} + \Delta\alpha_{had}^{(5)}$$
$$\Delta\alpha_{lept} = 0.0314977 \ [52] \qquad \Delta\alpha_{had}^{(5)} = 0.02758 \pm 0.00035$$
$$\alpha_s(m_Z) = 0.118 \pm 0.003$$

Inverting numerically the relation we get the constraint on m_H

Electroweak precision effects

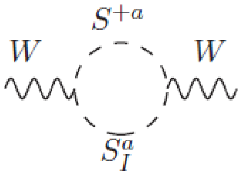


The term Δr_{new} depends on the mass of charged scalar and couplings λ_2, λ_3.

The color octet effects depend on the invariance of the scalar potential under SU(2) custodial symmetry.

1. SU(2)-symmetric $\lambda_2=2\lambda_3$ -> $\Delta\rho = 0$ $\Delta r_{new} > 0$; in order for m_H not to go below the experimental limit $m_S > 650$ GeV
2. SU(2) broken $\lambda_2 \neq 2\lambda_3$ -> $\Delta\rho \neq 0$; we can have $\Delta r_{new} < 0$; Higgs mass may increase

Scalars in adjoint representation of $SU(3)_C$ a = 1,...,8



x8 color factor

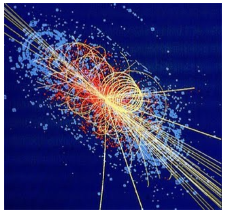
m_{S^+} (GeV)	$\Delta r_{new} \times 10^5$	m_H (GeV)
500	-8.41402	1340^{+415}_{-331}
600	-5.86394	718^{+399}_{-229}
700	-4.31749	405^{+188}_{-130}
800	-3.31021	277^{+132}_{-94}
900	-2.61799	211^{+105}_{-76}
1000	-2.12203	171^{+90}_{-64}
1500	-0.94466	100^{+61}_{-44}
2000	-0.53135	80^{+54}_{-37}

$\lambda_2 = 0.8$ $\lambda_3 = 0.3$

Color octet scalars with masses ~ 700-900 GeV allow a heavy Higgs in contrast with the SM fit.

For $m_S > 1500$ GeV the extra contribution becomes negligible, the octet decouples.

Conclusions



- Requiring the natural suppression of FCNCs in the extensions of the scalar sector of the SM the only allowed representations are $(1,2)_{1/2}$ and $(8,2)_{1/2}$.
- The presence of color octet scalars is interesting from the point of view of the LHC phenomenology.

The original contributions of this research have been:

- The 1-loop full analytic evaluation of new contributions to Wilson coefficients for $B \to X_s \gamma$

From numerical analysis we find two configurations that allow the existence of both heavy O(TeV) and light (>400 GeV) scalars.

- The 1-loop full analytic evaluation of new contributions to electroweak parameters Δr and $\Delta\rho$

The constraints on the Higgs mass heavily depend on the invariance under SU(2) custodial symmetry.

Extending the scalar sector by respecting the constraints of FCNCs through the principle of MFV, we obtain in a "fair" way the effect of raising the Higgs mass. For example, we may have

$m_S \sim 700\text{-}900$ GeV $\quad m_H \sim 400$ GeV