Electroweak precision constraints on 4th family quarks & leptons

J. Rohrwild

Institut für Theoretische Teilchenphysik und Kosmologie
RWTH Aachen

Flavour and the Fourth Family
Durham , September 2011

Electroweak World

- in the SM at first glance (at tree-level):

g g'		v
gauge couplings	and	a vev

straightforward relations to $\alpha(M_Z)$, G_F and M_Z ✓

Electroweak World

- in the SM at first glance (at tree-level):

$$g \qquad g' \qquad v$$

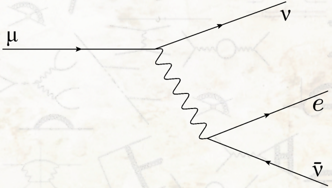
gauge couplings and a vev

straightforward relations to $\alpha(M_Z)$, G_F and M_Z ✓

- but of course physics is not so simple → quantum corrections entwine all sectors

$$\frac{G_F}{\sqrt{2}} = \frac{\pi\alpha}{2M_W \sin^2\Theta_W}\frac{1}{1-\Delta r}$$

where $\Delta r = \Delta r(m_t, m_H, \alpha_S, \ldots)$



Electroweak World

- in the SM at first glance (at tree-level):

g	g'	v

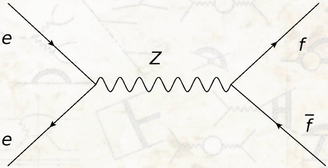
gauge couplings and a vev

straightforward relations to $\alpha(M_Z)$, G_F and M_Z ✓

- but of course physics is not so simple $\rightarrow$ quantum corrections entwine all sectors

effective Z boson couplings

$$g_V^f \rightarrow g_V^f + \Delta g_V^f$$
$$g_A^f \rightarrow g_A^f + \Delta g_A^f$$



effective ew mixing angle (for $f = e$):

$$\sin^2\theta_{eff} = \frac{1}{4}\left(1 - \mathrm{Re}\frac{g_A^e}{g_V^e}\right) = \kappa\left(1 - \frac{M_W^2}{M_Z^2}\right)$$

Electroweak World

- in the SM at first glance (at tree-level):

$g \quad g' \quad v$

gauge couplings and a vev

straightforward relations to $\alpha(M_Z)$, G_F and M_Z ✓

- but of course physics is not so simple $\rightarrow$ Yukawa sector

Yukawa sector
$\rightarrow$ gives fermions masses and thus provides a second 'natural' set of eigenstates
$\rightarrow$ introduces the CKM and PMNS matrices

- we need at least $2(N_F - 1)^2$ additional parameters to describe the W couplings ☹
- we can learn so much from flavour physics ☺

Electroweak Observables

Electroweak Observables

- non-Z pole observables

Quantity	Value	Standard Model	Pull	Dev.
m_t [GeV]	173.1 ± 1.3	173.2 ± 1.3	-0.1	-0.5
M_W [GeV]	80.420 ± 0.031	80.384 ± 0.014	1.2	1.5
	80.376 ± 0.033		-0.2	0.1
g_L^2	0.3027 ± 0.0018	0.30399 ± 0.00017	-0.7	-0.6
g_R^2	0.0308 ± 0.0011	0.03001 ± 0.00002	0.7	0.7
$g_V^{\nu e}$	-0.040 ± 0.015	-0.0398 ± 0.0003	0.0	0.0
$g_A^{\nu e}$	-0.507 ± 0.014	-0.5064 ± 0.0001	0.0	0.0
$Q_W(e)$	-0.0403 ± 0.0053	-0.0473 ± 0.0005	1.3	1.2
$Q_W(\mathrm{Cs})$	-73.20 ± 0.35	-73.15 ± 0.02	-0.1	-0.1
$Q_W(\mathrm{Tl})$	-116.4 ± 3.6	-116.76 ± 0.04	0.1	0.1
τ_τ [fs]	291.09 ± 0.48	290.02 ± 2.09	0.5	0.5
$\frac{\Gamma(b \to s\gamma)}{\Gamma(b \to X e\nu)}$	$\left(3.38^{+0.51}_{-0.44}\right) \times 10^{-3}$	$(3.11 \pm 0.07) \times 10^{-3}$	0.6	0.6
$\frac{1}{2}(g_\mu - 2 - \frac{\alpha}{\pi})$	$(4511.07 \pm 0.77) \times 10^{-9}$	$(4509.13 \pm 0.08) \times 10^{-9}$	2.5	2.5

Electroweak Observables

- non-Z pole observables
  - many low energy observables such as g_L and g_R in Fermi theory

Quantity	Value	Standard Model	Pull	Dev.
m_t [GeV]	173.1 ± 1.3	173.2 ± 1.3	-0.1	-0.5
M_W [GeV]	80.420 ± 0.031	80.384 ± 0.014	1.2	1.5
	80.376 ± 0.033		-0.2	0.1
g_L^2	0.3027 ± 0.0018	0.30399 ± 0.00017	-0.7	-0.6
g_R^2	0.0308 ± 0.0011	0.03001 ± 0.00002	0.7	0.7
$g_V^{\nu e}$	-0.040 ± 0.015	-0.0398 ± 0.0003	0.0	0.0
$g_A^{\nu e}$	-0.507 ± 0.014	-0.5064 ± 0.0001	0.0	0.0
$Q_W(e)$	-0.0403 ± 0.0053	-0.0473 ± 0.0005	1.3	1.2
$Q_W(\mathrm{Cs})$	-73.20 ± 0.35	-73.15 ± 0.02	-0.1	-0.1
$Q_W(\mathrm{Tl})$	-116.4 ± 3.6	-116.76 ± 0.04	0.1	0.1
τ_τ [fs]	291.09 ± 0.48	290.02 ± 2.09	0.5	0.5
$\frac{\Gamma(b\to s\gamma)}{\Gamma(b\to X e\nu)}$	$\left(3.38^{+0.51}_{-0.44}\right) \times 10^{-3}$	$(3.11 \pm 0.07) \times 10^{-3}$	0.6	0.6
$\frac{1}{2}(g_\mu - 2 - \frac{\alpha}{\pi})$	$(4511.07 \pm 0.77) \times 10^{-9}$	$(4509.13 \pm 0.08) \times 10^{-9}$	2.5	2.5

Electroweak Observables

- non-Z pole observables
  - many low energy observables such as g_L and g_R
- Z pole observables

Quantity	Value	Standard Model	Pull	Dev.
M_Z [GeV]	91.1876 ± 0.0021	91.1874 ± 0.0021	0.1	0.0
Γ_Z [GeV]	2.4952 ± 0.0023	2.4954 ± 0.0009	−0.1	0.1
$\Gamma(\text{had})$ [GeV]	1.7444 ± 0.0020	1.7418 ± 0.0009	—	—
$\Gamma(\text{inv})$ [MeV]	499.0 ± 1.5	501.69 ± 0.07	—	—
$\Gamma(\ell^+\ell^-)$ [MeV]	83.984 ± 0.086	84.005 ± 0.015	—	—
σ_{had}[nb]	41.541 ± 0.037	41.484 ± 0.008	1.5	1.5
R_e	20.804 ± 0.050	20.735 ± 0.010	1.4	1.4
R_μ	20.785 ± 0.033	20.735 ± 0.010	1.5	1.6
R_τ	20.764 ± 0.045	20.780 ± 0.010	−0.4	−0.3
R_b	0.21629 ± 0.00066	0.21578 ± 0.00005	0.8	0.8
R_c	0.1721 ± 0.0030	0.17224 ± 0.00003	0.0	0.0
$A_{FB}^{(0,e)}$	0.0145 ± 0.0025	0.01633 ± 0.00021	−0.7	−0.7
$A_{FB}^{(0,\mu)}$	0.0169 ± 0.0013		0.4	0.6
$A_{FB}^{(0,\tau)}$	0.0188 ± 0.0017		1.5	1.6
$A_{FB}^{(0,b)}$	0.0992 ± 0.0016	0.1034 ± 0.0007	−2.7	−2.3
$A_{FB}^{(0,c)}$	0.0707 ± 0.0035	0.0739 ± 0.0005	−0.9	−0.8
$A_{FB}^{(0,s)}$	0.0976 ± 0.0114	0.1035 ± 0.0007	−0.6	−0.4
$\bar{s}_\ell^2(A_{FB}^{(0,q)})$	0.2324 ± 0.0012	0.23146 ± 0.00012	0.8	0.7
	0.2316 ± 0.0018		0.1	0.0
A_e	0.15138 ± 0.00216	0.1475 ± 0.0010	1.8	2.2
	0.1544 ± 0.0060		1.1	1.3
	0.1498 ± 0.0049		0.5	0.6
A_μ	0.142 ± 0.015		−0.4	−0.3
A_τ	0.136 ± 0.015		−0.8	−0.7
	0.1439 ± 0.0043		−0.8	−0.7
A_b	0.923 ± 0.020	0.9348 ± 0.0001	−0.6	−0.6
A_c	0.670 ± 0.027	0.6680 ± 0.0004	0.1	0.1
A_s	0.895 ± 0.091	0.9357 ± 0.0001	−0.4	−0.4

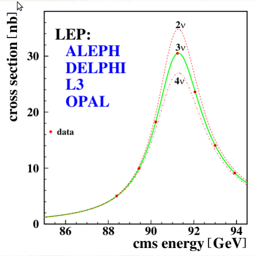
Electroweak Observables

- non-Z pole observables
  - many low energy observables such as g_L and g_R
- Z pole observables
  - very high precision

Quantity	Value	Standard Model	Pull	Dev.
M_Z [GeV]	91.1876 ± 0.0021	91.1874 ± 0.0021	0.1	0.0
Γ_Z [GeV]	2.4952 ± 0.0023	2.4954 ± 0.0009	−0.1	0.1
$\Gamma(\text{had})$ [GeV]	1.7444 ± 0.0020	1.7418 ± 0.0009	—	—
$\Gamma(\text{inv})$ [MeV]	499.0 ± 1.5	501.69 ± 0.07	—	—
$\Gamma(\ell^+\ell^-)$ [MeV]	83.984 ± 0.086	84.005 ± 0.015	—	—
σ_{had}[nb]	41.541 ± 0.037	41.484 ± 0.008	1.5	1.5
R_e	20.804 ± 0.050	20.735 ± 0.010	1.4	1.4
R_μ	20.785 ± 0.033	20.735 ± 0.010	1.5	1.6
R_τ	20.764 ± 0.045	20.780 ± 0.010	−0.4	−0.3
R_b	0.21629 ± 0.00066	0.21578 ± 0.00005	0.8	0.8
R_c	0.1721 ± 0.0030	0.17224 ± 0.00003	0.0	0.0
$A_{FB}^{(0,e)}$	0.0145 ± 0.0025	0.01633 ± 0.00021	−0.7	−0.7
$A_{FB}^{(0,\mu)}$	0.0169 ± 0.0013		0.4	0.6
$A_{FB}^{(0,\tau)}$	0.0188 ± 0.0017		1.5	1.6
$A_{FB}^{(0,b)}$	0.0992 ± 0.0016	0.1034 ± 0.0007	−2.7	−2.3
$A_{FB}^{(0,c)}$	0.0707 ± 0.0035	0.0739 ± 0.0005	−0.9	−0.8
$A_{FB}^{(0,s)}$	0.0976 ± 0.0114	0.1035 ± 0.0007	−0.6	−0.4
$\bar{s}_\ell^2(A_{FB}^{(0,q)})$	0.2324 ± 0.0012	0.23146 ± 0.00012	0.8	0.7
	0.2316 ± 0.0018		0.1	0.0
A_e	0.15138 ± 0.00216	0.1475 ± 0.0010	1.8	2.2
	0.1544 ± 0.0060		1.1	1.3
	0.1498 ± 0.0049		0.5	0.6
A_μ	0.142 ± 0.015		−0.4	−0.3
A_τ	0.136 ± 0.015		−0.8	−0.7
	0.1439 ± 0.0043		−0.8	−0.7
A_b	0.923 ± 0.020	0.9348 ± 0.0001	−0.6	−0.6
A_c	0.670 ± 0.027	0.6680 ± 0.0004	0.1	0.1
A_s	0.895 ± 0.091	0.9357 ± 0.0001	−0.4	−0.4

Electroweak Observables

- non-Z pole observables
  - many low energy observables such as g_L and g_R
- Z pole observables
  - very high precision
  - Z line shape:
    $N_\nu = 2.9840 \pm 0.0082$
    mass limit $m_{\nu_4} \geq \frac{M_Z}{2}$



- $G_F = 1.166364(5) \times 10^{-5}\ \text{GeV}^{-2}$

Quantity	Value	Standard Model	Pull	Dev.
M_Z [GeV]	91.1876 ± 0.0021	91.1874 ± 0.0021	0.1	0.0
Γ_Z [GeV]	2.4952 ± 0.0023	2.4954 ± 0.0009	−0.1	0.1
$\Gamma(\text{had})$ [GeV]	1.7444 ± 0.0020	1.7418 ± 0.0009	—	—
$\Gamma(\text{inv})$ [MeV]	499.0 ± 1.5	501.69 ± 0.07	—	—
$\Gamma(\ell^+\ell^-)$ [MeV]	83.984 ± 0.086	84.005 ± 0.015	—	—
σ_{had}[nb]	41.541 ± 0.037	41.484 ± 0.008	1.5	1.5
R_e	20.804 ± 0.050	20.735 ± 0.010	1.4	1.4
R_μ	20.785 ± 0.033	20.735 ± 0.010	1.5	1.6
R_τ	20.764 ± 0.045	20.780 ± 0.010	−0.4	−0.3
R_b	0.21629 ± 0.00066	0.21578 ± 0.00005	0.8	0.8
R_c	0.1721 ± 0.0030	0.17224 ± 0.00003	0.0	0.0
$A_{FB}^{(0,e)}$	0.0145 ± 0.0025	0.01633 ± 0.00021	−0.7	−0.7
$A_{FB}^{(0,\mu)}$	0.0169 ± 0.0013		0.4	0.6
$A_{FB}^{(0,\tau)}$	0.0188 ± 0.0017		1.5	1.6
$A_{FB}^{(0,b)}$	0.0992 ± 0.0016	0.1034 ± 0.0007	−2.7	−2.3
$A_{FB}^{(0,c)}$	0.0707 ± 0.0035	0.0739 ± 0.0005	−0.9	−0.8
$A_{FB}^{(0,s)}$	0.0976 ± 0.0114	0.1035 ± 0.0007	−0.6	−0.4
$\bar{s}_\ell^2(A_{FB}^{(0,q)})$	0.2324 ± 0.0012	0.23146 ± 0.00012	0.8	0.7
	0.2316 ± 0.0018		0.1	0.0
A_e	0.15138 ± 0.00216	0.1475 ± 0.0010	1.8	2.2
	0.1544 ± 0.0060		1.1	1.3
	0.1498 ± 0.0049		0.5	0.6
A_μ	0.142 ± 0.015		−0.4	−0.3
A_τ	0.136 ± 0.015		−0.8	−0.7
	0.1439 ± 0.0043		−0.8	−0.7
A_b	0.923 ± 0.020	0.9348 ± 0.0001	−0.6	−0.6
A_c	0.670 ± 0.027	0.6680 ± 0.0004	0.1	0.1
A_s	0.895 ± 0.091	0.9357 ± 0.0001	−0.4	−0.4

BSM Physics

- basically all Z pole observables (width, asymmetries) can be expressed in terms of the effective couplings $g^f_{A/V}$ (e.g. γ photon exchange diagram is strongly suppressed):

$$\Gamma\left(Z \to \bar{q}q\right) = \alpha M_Z \left[(g^q_V)^2 + (g^q_A)^2 \right]$$

$$A^{(q)}_{FB} = \frac{3}{4} \mathcal{A}_e \mathcal{A}_q$$

$$\mathcal{A}_q = \frac{g^q_V g^q_A}{(g^q_V)^2 + (g^q_A)^2}$$

- electroweak corrections to G_F, i.e. a one loop Δr can be approximated via self-energy expressions:

Böhm

$$\Delta r \approx \Pi_{AA}(0) + \frac{\Sigma^{WW}_T(0) - \mathrm{Re}\Sigma^{WW}_T(M_W)}{M^2_W} - \frac{c^2_W}{s^2_W} \mathrm{Re} \left(\frac{\Sigma^{ZZ}_T(M_Z)}{M^2_Z} - \frac{\Sigma^{WW}_T(M_W)}{M^2_W} \right)$$
$$+ \frac{2c^2_W}{s^2_W} \frac{\Sigma^{AZ}_T(0)}{M^2_Z} + \frac{\alpha}{4\pi s^2_W} \left(6 + \frac{7 - 4s^2_W}{2s^2_W} \log c^2_w \right)$$

BSM Physics

- Experimental precision in better then the one-loop quantum effects
- EWPO have been (the bane of) a challenge for a many new physics models
  - technicolor models
  - extra generations
  - RS models
  - ...
- How precise are the SM calculations for the major electroweak observables?
  e.g. $Z \to \bar{q}q$

  α_s^4 (massless QCD) , QCD corrections to m_q^2 , mixed $\alpha\alpha_s$ contributions

  also $\mathcal{O}(\alpha^2)$ and quartic in m_t

BSM Physics

- Experimental precision in better then the one-loop quantum effects
- EWPO have been (the bane of) a challenge for a many new physics models
  - technicolor models
  - extra generations
  - RS models
  - ...
- Determining the impact of a NP model on the observables is hard and tedious

BSM Physics

- Experimental precision in better then the one-loop quantum effects
- EWPO have been (the bane of) a challenge for a many new physics models
  - technicolor models
  - extra generations
  - RS models
  - ...
- if BSM physics:
  1. doesn't change/extend the (electroweak) gauge group of the SM
  2. does not couple to light fermions
  3. has a scale above the electroweak scale

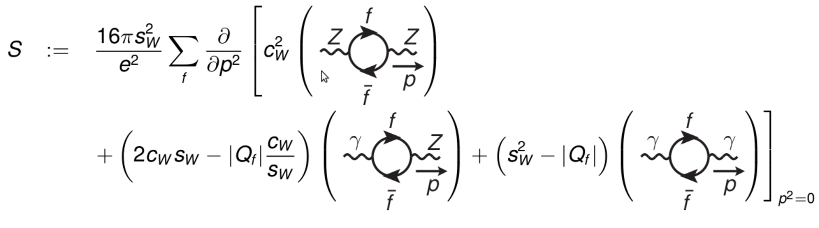
  then effects on the electroweak observables are captured by gauge boson self-energy graphs

  $\rightarrow$ introduce oblique parameters S, T and U — Peskin '90

  $\rightarrow$ or alternatively $\hat{\epsilon}_{1/2/3}$ and $h_{V/AZ/AW}$ — Kennedy '90, Altarelli '90

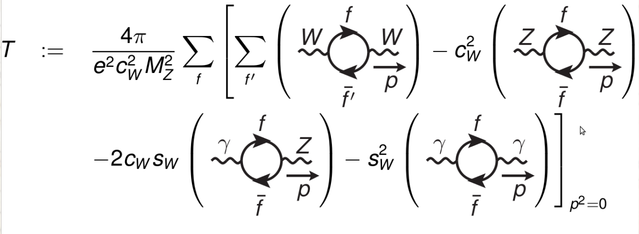
Approximation of New Physics Effects

- S parameter (breaking of axial $SU(2)$)



$+$ bosonic contributions to the self energy

- T parameter (breaking of vector $SU(2)$)



$+$ bosonic contributions to the self energy

Approximation of New Physics Effects

- if BSM physics
  1. doesn't change/extend the (electroweak) gauge group of the SM
  2. does not couple to light fermions
  3. has a scale above the electroweak scale

  then effects on the electroweak observables are captured by gauge boson self-energy graphs
  → introduce oblique parameters S, T and U

- the shift in the Z couplings is given by

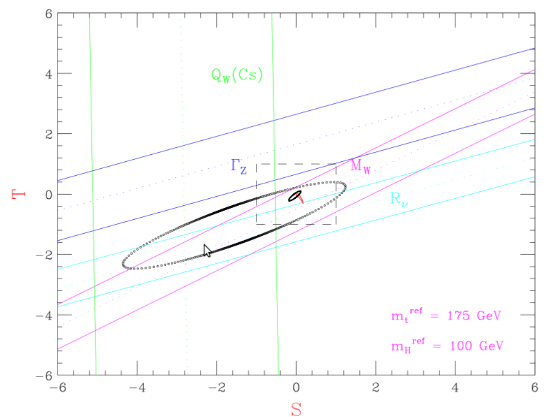
$$\delta g_V^q = \frac{\alpha}{16 c_W s_W^3}\left[2I_3^q S - 4[(c_W^2 - s_W^2)I_3^q + 2s_W^2 Q^q]T - \left(\frac{c_W^2 - s_W^2}{s_W^2} I_3^q + 2Q^q\right)U\right]$$

$$\delta g_A^q = \frac{\alpha}{16 c_W s_W^3}\left[2S - \frac{c_W^2 - s_W^2}{s_W^2}(4s_W^2 T + U)\right] I_3^q$$

- oblique parameters can be fitted directly to experiment
  → easy to use

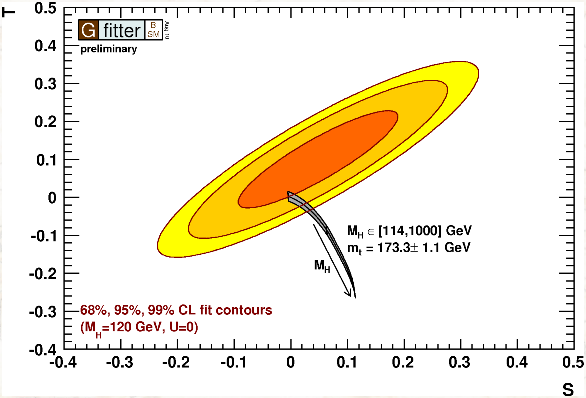
S and T

- before looking at the bounds for 4th generation scenarios a look at the oblique observables
- pre LEP vs post LEP



S and T

- before looking at the bounds for 4th generation scenarios a look at the oblique observables
- current status (relative to the SM)



$$S = 0.02 \pm 0.11$$
$$T = 0.05 \pm 0.12$$
$$U = 0.07 \pm 0.12$$

Reference point $m_t = 173.1$ GeV and $M_H = 120$ GeV

Electroweak and SM4

- SM with a fourth generation
  1. doesn't change/extend the (electroweak) gauge group of the SM ✓
  2. does not couple to light fermions (✓)
  3. has a scale above the electroweak scale (✓)

Electroweak and SM4

- SM with a fourth generation
  1. doesn't change/extend the (electroweak) gauge group of the SM ✓
  2. does not couple to light fermions (✓)
  3. has a scale above the electroweak scale (✓)

S and T parameter in SM4

- contribution to S

$$S_f = \frac{N_c}{6\pi} \sum_{(U,D)} \left[1 - \frac{2}{3} \ln\left(\frac{m_U}{m_D}\right) \right] + \frac{1}{6\pi} \sum_{(\nu,l)} \left[1 + 2\ln\left(\frac{m_\nu}{m_l}\right) \right] \quad \text{(Dirac neutrinos)}$$

- contribution to T

$$T_f = \frac{N_c}{16\pi s_W^2 c_W^2 M_Z^2} \left[\sum_{i=U,D} m_i^2 - 4 \sum_{U,D} \left| V_{UD}^{(\mathrm{CKM})} \right|^2 \frac{m_U^2 m_D^2}{m_U^2 - m_D^2} \ln\left(\frac{m_U}{m_D}\right) \right]$$

$$+ \frac{1}{16\pi s_W^2 c_W^2 M_Z^2} \left[\sum_{i=\nu,l} m_i^2 - 4 \sum_{\nu,l} \left| V_{\nu l}^{(\mathrm{PMNS})} \right|^2 \frac{m_\nu^2 m_l^2}{m_\nu^2 - m_l^2} \ln\left(\frac{m_\nu}{m_l}\right) \right] \quad \geq 0 \text{ (Dirac)}$$

S and T parameter in SM4

- S with Majorana neutrinos

Bertolini '91, Kniehl '93

$$S_f = \frac{N_c}{6\pi} \sum_{(U,D)} \left[1 - \frac{2}{3} \ln\left(\frac{m_U}{m_D}\right) \right] + S_M \qquad S_M \gtrsim 0$$

- T with Majorana neutrinos

Gates '91, Kniehl '93

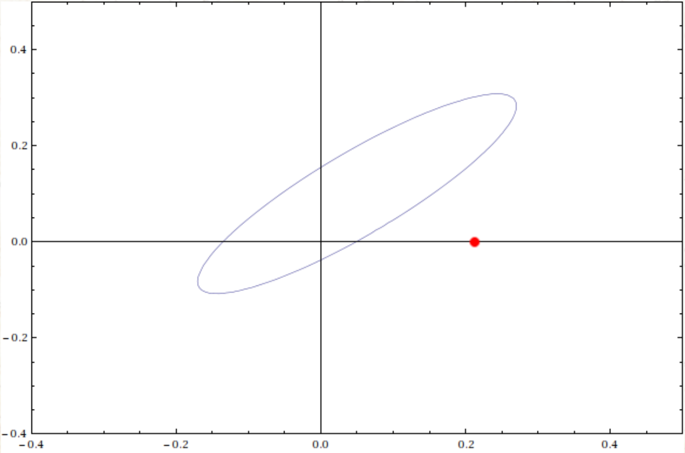
$$T_f = \frac{N_c}{16\pi s_W^2 c_W^2 M_Z^2} \left[\sum_{i=U,D} m_i^2 - 4 \sum_{U,D} \left| V_{UD}^{(\text{CKM})} \right|^2 \frac{m_U^2 m_D^2}{m_U^2 - m_D^2} \ln\left(\frac{m_U}{m_D}\right) \right] + T_M \qquad T_M \gtrsim 0$$

more on neutrinos $\rightarrow$ talk by Heinrich Päs

SFB TR9

Constraints from *S* and *T* parameter for SM4

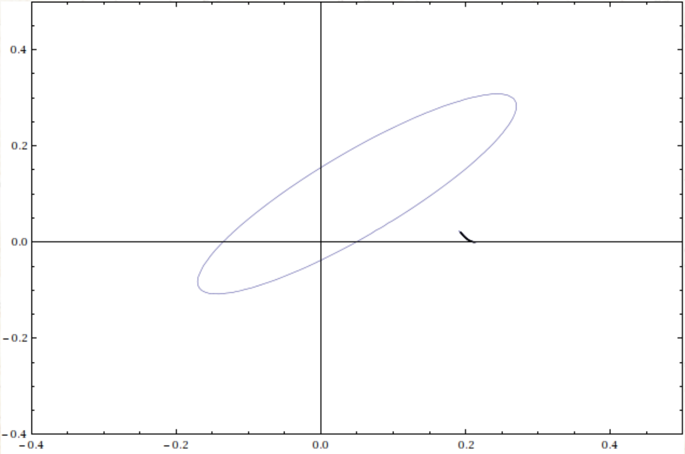
- full degeneracy (trivial flavour aspects)



Constraints from S and T parameter for SM4

- lepton mass splitting (trivial flavour aspects)

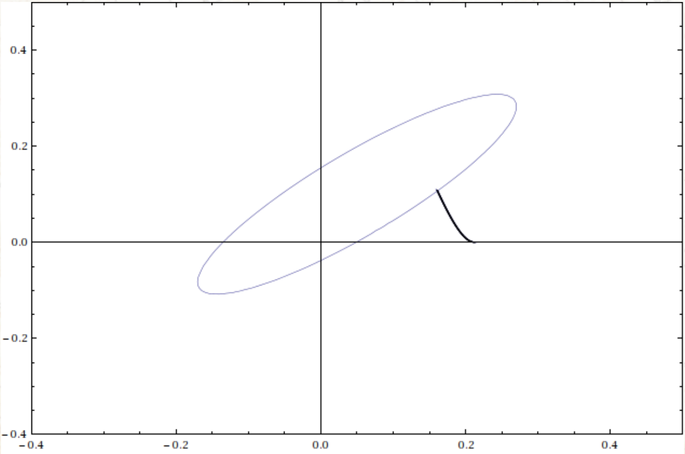
e.g. Okun; Kribs et. al '07



Constraints from *S* and *T* parameter for SM4

- lepton mass splitting (trivial flavour aspects)

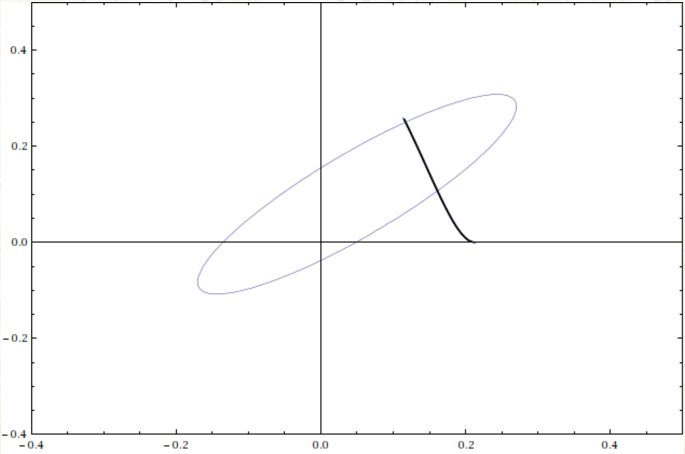
e.g. Okun; Kribs et. al '07



Constraints from *S* and *T* parameter for SM4

- lepton mass splitting (trivial flavour aspects)

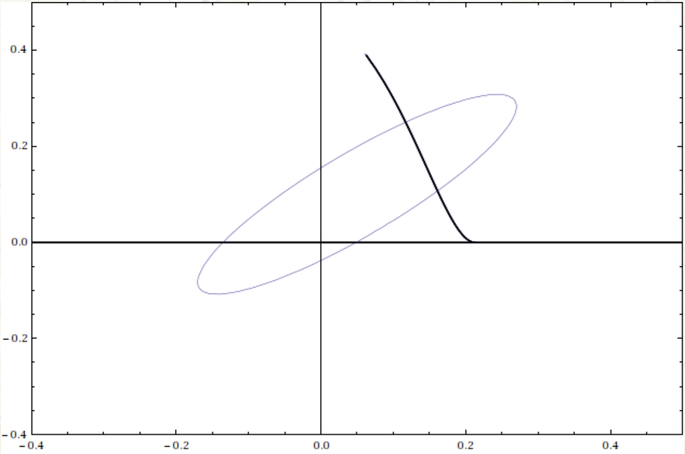
e.g. Okun; Kribs et. al '07



Constraints from *S* and *T* parameter for SM4

- lepton mass splitting (trivial flavour aspects)

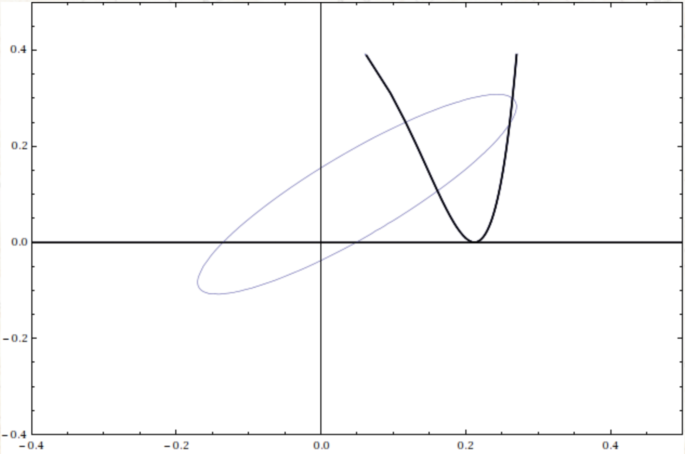
e.g. Okun; Kribs et. al '07



Constraints from *S* and *T* parameter for SM4

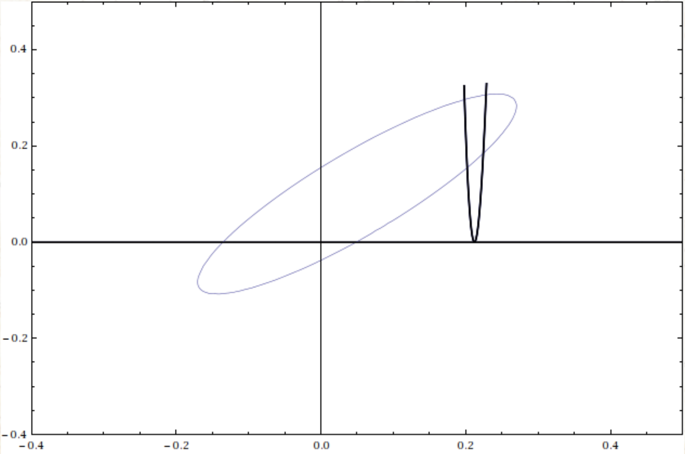
- lepton mass splitting (trivial flavour aspects)

e.g. Okun; Kribs et. al ’07



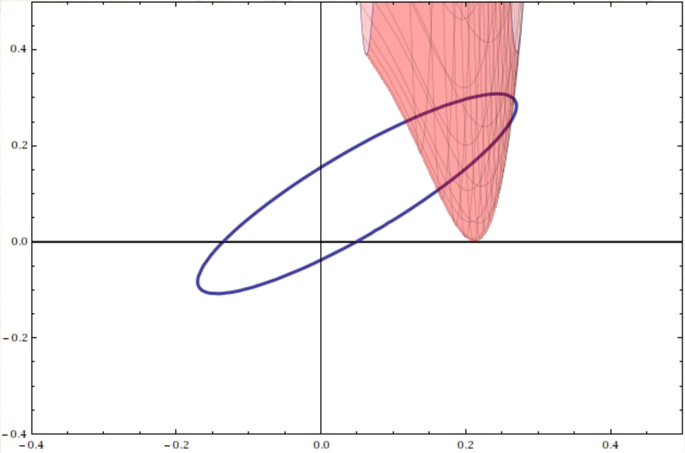
Constraints from *S* and *T* parameter for SM4

- quark mass splitting (trivial flavour aspects)



Constraints from *S* and *T* parameter for SM4

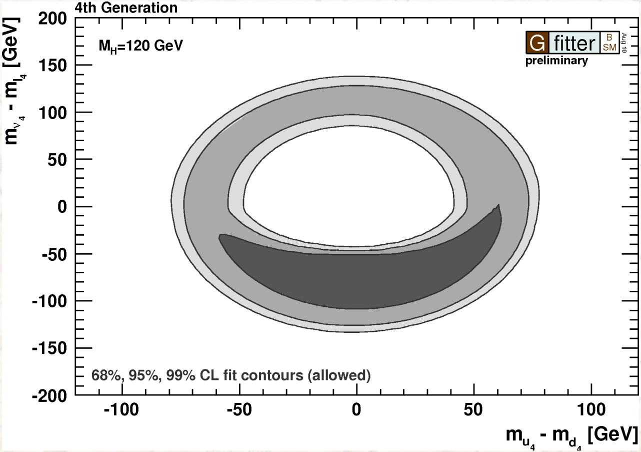
- quark and lepton mass splitting (trivial flavour aspects)



also Erler '10

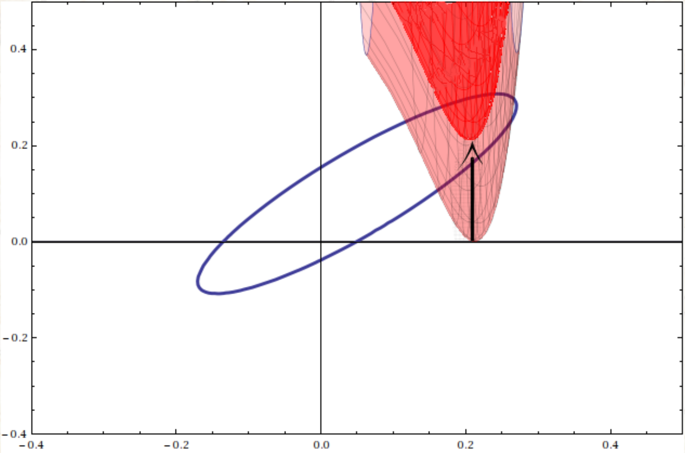
Constraints from *S* and *T* parameter for SM4

- quark and lepton mass splitting (trivial flavour aspects)



Constraints from S and T parameter for SM4

- quark and lepton mass splitting (with mixing matrices)

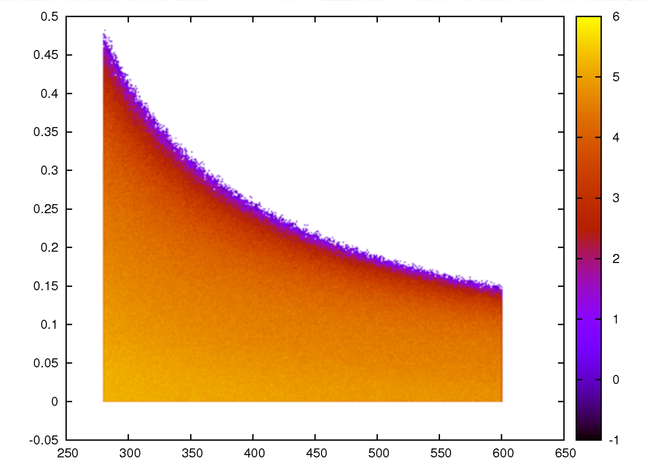


$\rightarrow$ strong bounds on quark mixing, esp. θ_{34}
$\rightarrow$ correlates masses and CKM elements; larger m_t' $\rightarrow$ smaller mixing

more one limits/fits for the CKM elements $\rightarrow$ talk by Otto Eberhardt

Constraints from *S* and *T* parameter for SM4

Eberhardt '10

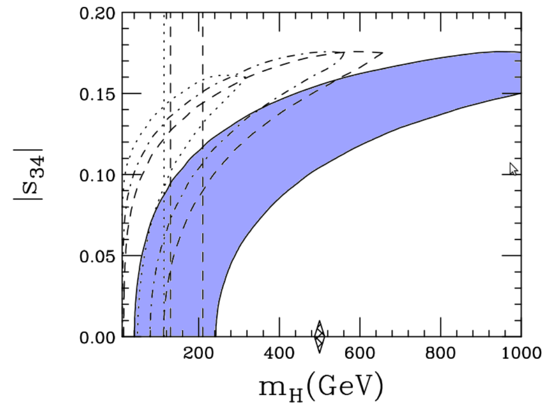


Fixed Higgs mass of 120 GeV

Constraints from *S* and *T* parameter for SM4

Correlation of mixing/masses and mass splitting is non-trivial especially if the Higgs mass is also free

Chanowitz '10



only for selected masses: $m_{t'} = 500$ GeV, three different lepton mass splittings

Subtleties of SM4

- The oblique parameters parameterize new physics in Z pole observables
- The slight breaking of the requirements in the SM4 scenario can have two effects
  1. modification of low energy observables used as an input of the S, T, U fit
  2. contributions beyond the self-energy parts

Subtleties of SM4

- The oblique parameters parameterize new physics in Z pole observables
- The slight breaking of the requirements in the SM4 scenario can have two effects
  1. modification of low energy observables used as an input of the S, T, U fit
  2. contributions beyond the self-energy parts

An potential example for (1) would be the extraction of G_F with general PMNS matrix
$\rightarrow$ increased uncertainty?

$\rightarrow$ see talk by Andreas Menzel tomorrow

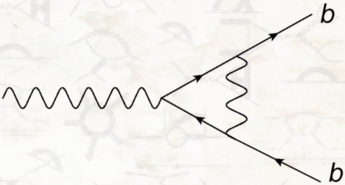
Deviations from the oblique formulas

- the well known candidate for additional corrections: R_b

see e.g. Alwall '99, Chanowitz '09/'10, ...

$$R_b = \frac{\Gamma(Z \to \bar{b}b)}{\Gamma(Z \to \text{hadrons})}$$

> most precise of the R_q's
> V_{tb}, $V_{t'b}$ are the least constrained matrix elements

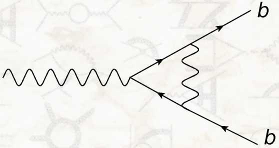


Deviations from the oblique formulas

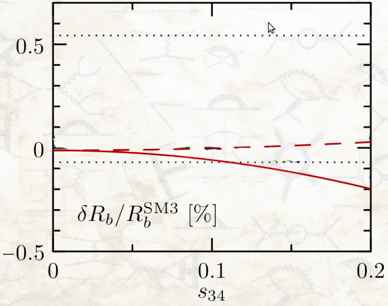
- the well known candidate for additional corrections: R_b

see e.g. Alwall '99, Chanowitz '09/'10, ...

$$R_b = \frac{\Gamma(Z \to \bar{b}b)}{\Gamma(Z \to \text{hadrons})}$$



$>$ most precise of the R_q's
$>$ V_{tb}, $V_{t'b}$ are the least constrained matrix elements

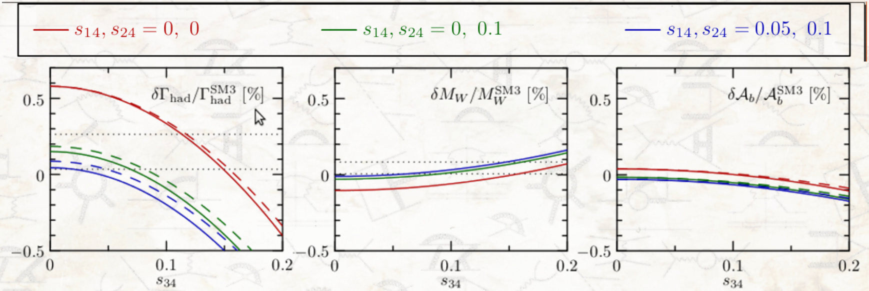


full 1-loop corrections

González

Deviations from the oblique formulas

- non-oblique corrections to other Z Pole observables



for $m_t' = 400$ GeV and 16 GeV splitting, $m_H = 600$ GeV.

- overall effect of non-oblique corrections is small
- only R_b (and Γ_{had}) are effected in the per mille range

Summery

- EWPO provide very stringent constraints for any new physics model
- the “oblique method” has two main advantages:
  1. assess the effect of a NP in the electroweak sector without the need for a “full” analysis
  2. allows visualization of the effect of individual parameters on the electroweak fit
- EWPO constrain the SM4
  - strong limits on the maximal mass splitting of quark (~ 85 GeV for $M_H = 120$ GeV) and leptons (~ 140 GeV for $M_H = 120$ GeV)
  - constrains CKM mixing of the 4th generation with the first three
    $\rightarrow$ most important for the $3-4$ mixing
    $\rightarrow$ *higher* masses lead to *lower* a upper bound
- mixing allows for a degenerate family
- non-oblique effects in R_B are sizable
- for a reliable “probabilistic” interpretation of a given parameter point one might want to consider these effects