Limits of Custodial Symmetry

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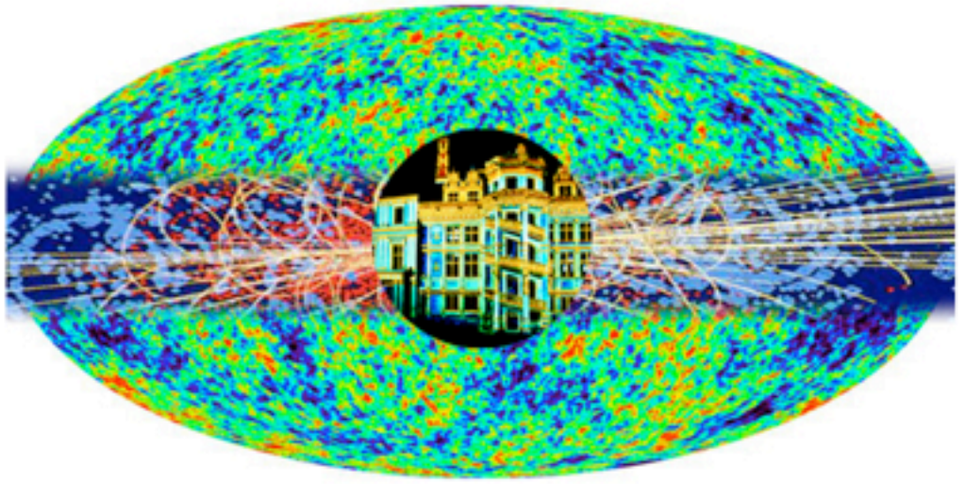
22nd Rencontres de Blois

Particle Physics and Cosmology

first results from the LHC

Château Royal de Blois



15th - 20th July, 2010

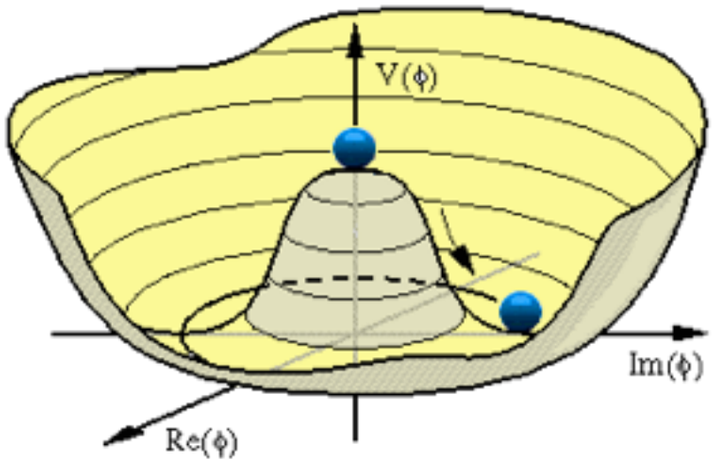
Outline

- Custodial symmetry
  - LEP/SLD Data
- Custodial symmetry for the top-quark
- The Doublet-Extended Standard Model
  - Constraints
- Conclusions and Questions
- Remark: χSB in Higgsless Models

Custodial Symmetry: The SM Higgs

A Fundamental Scalar Doublet:

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \quad ,$$



with potential:

$$V(\phi) = \lambda \left(\phi^\dagger \phi - \frac{v^2}{2} \right)^2$$

is employed both to break the electroweak symmetry and to generate masses for the fermions in the Standard Model.

Custodial Symmetry: SU(2)$_V$

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

Due to residual $SU(2)_V$ "custodial symmetry" for $g' \to 0$, the $SU(2)_L$ gauge bosons are degenerate.

This, plus $m_\gamma = 0$, tells us

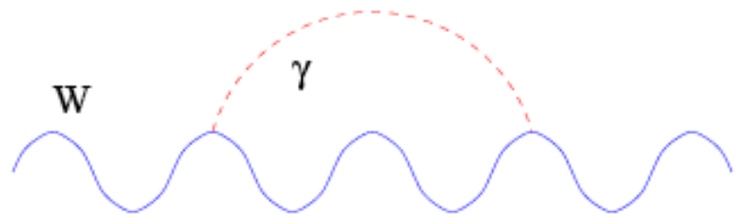
$$M^2 = \frac{v^2}{2} \begin{pmatrix} g^2 & & & \\ & g^2 & & \\ & & g^2 & -gg' \\ & & -gg' & g'^2 \end{pmatrix} ,$$

and hence

$$\rho \equiv \frac{M_W^2}{M_Z^2 \cos^2 \theta_W} = 1 \ .$$

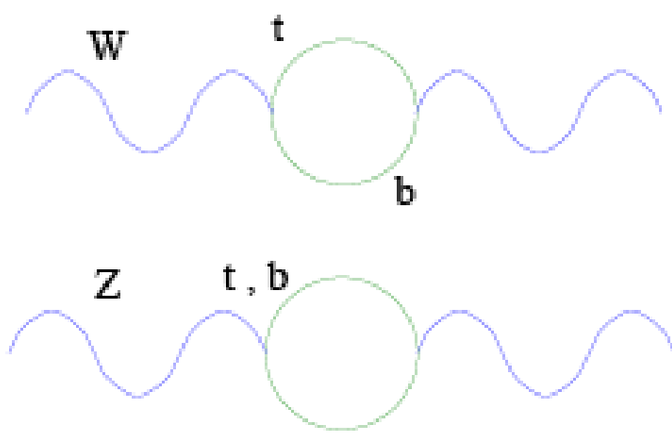
Violations of Custodial Symmetry

Electromagnetism: $\mathcal{O}(\alpha)$ corrections to $\Delta\rho$ from



Yukawa Couplings:

$$\bar{\psi}_L \Phi \begin{pmatrix} y_t & \\ & y_b \end{pmatrix} \begin{pmatrix} t_R \\ b_R \end{pmatrix}$$



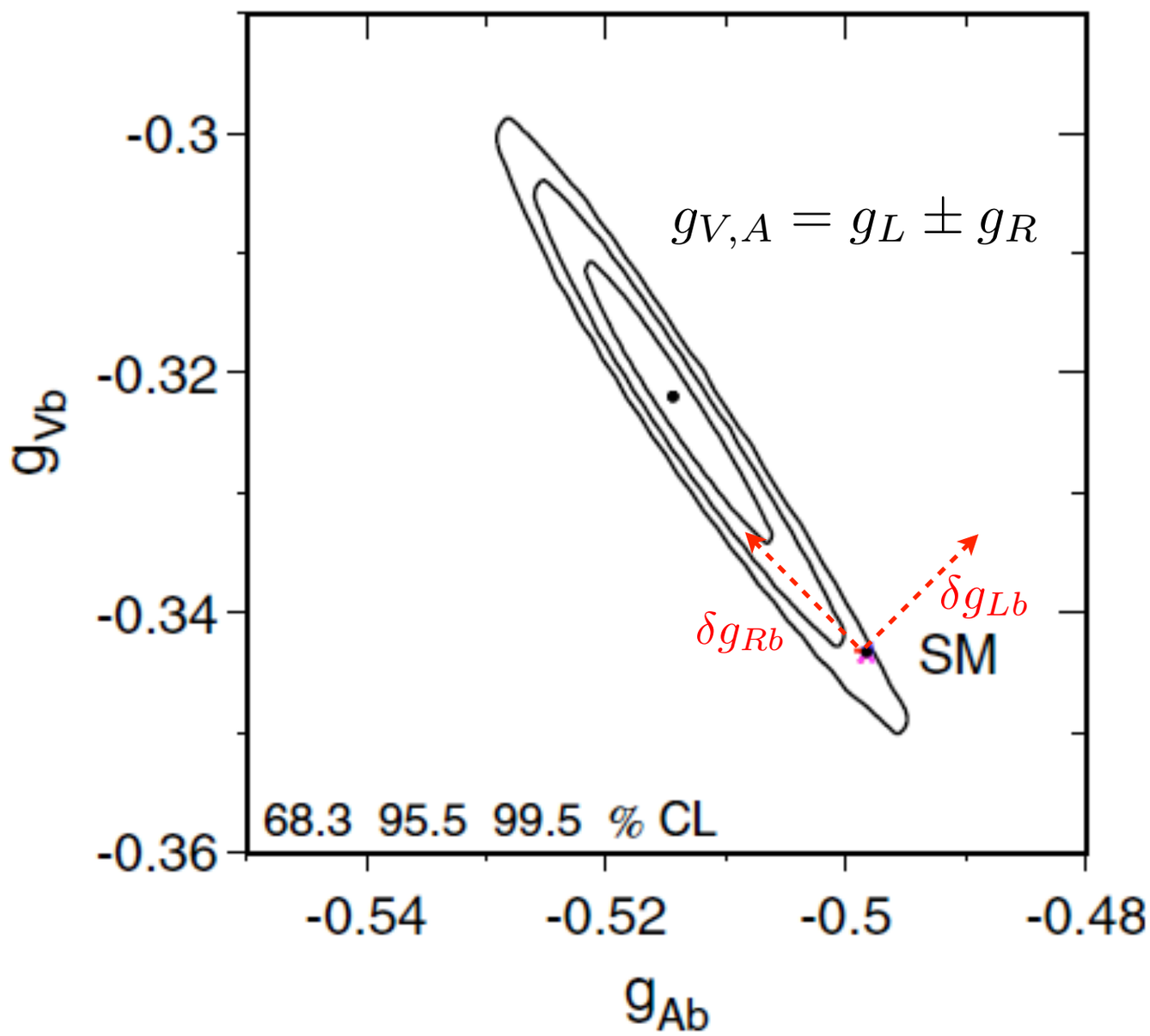
$$\Delta\rho \approx \frac{3y_t^2}{32\pi^2}$$

Nota Bene: Custodial symmetry is accidental. It applies to $SU(2)_L \times U(1)_Y$ invariant terms of dimension 4 or less ($g' \to 0$). Can be violated by terms of higher dimension, *e.g.*

$$(\phi^\dagger D^\mu \phi)(\phi^\dagger D_\mu \phi) = \frac{1}{4}\left(\mathrm{Tr}\,\sigma_3 \Phi^\dagger D^\mu \Phi\right)\left(\mathrm{Tr}\,\sigma_3 \Phi^\dagger D_\mu \Phi\right)$$

Custodial Symmetry is an important part of any theory of EWSB!

LEP/SLD Data

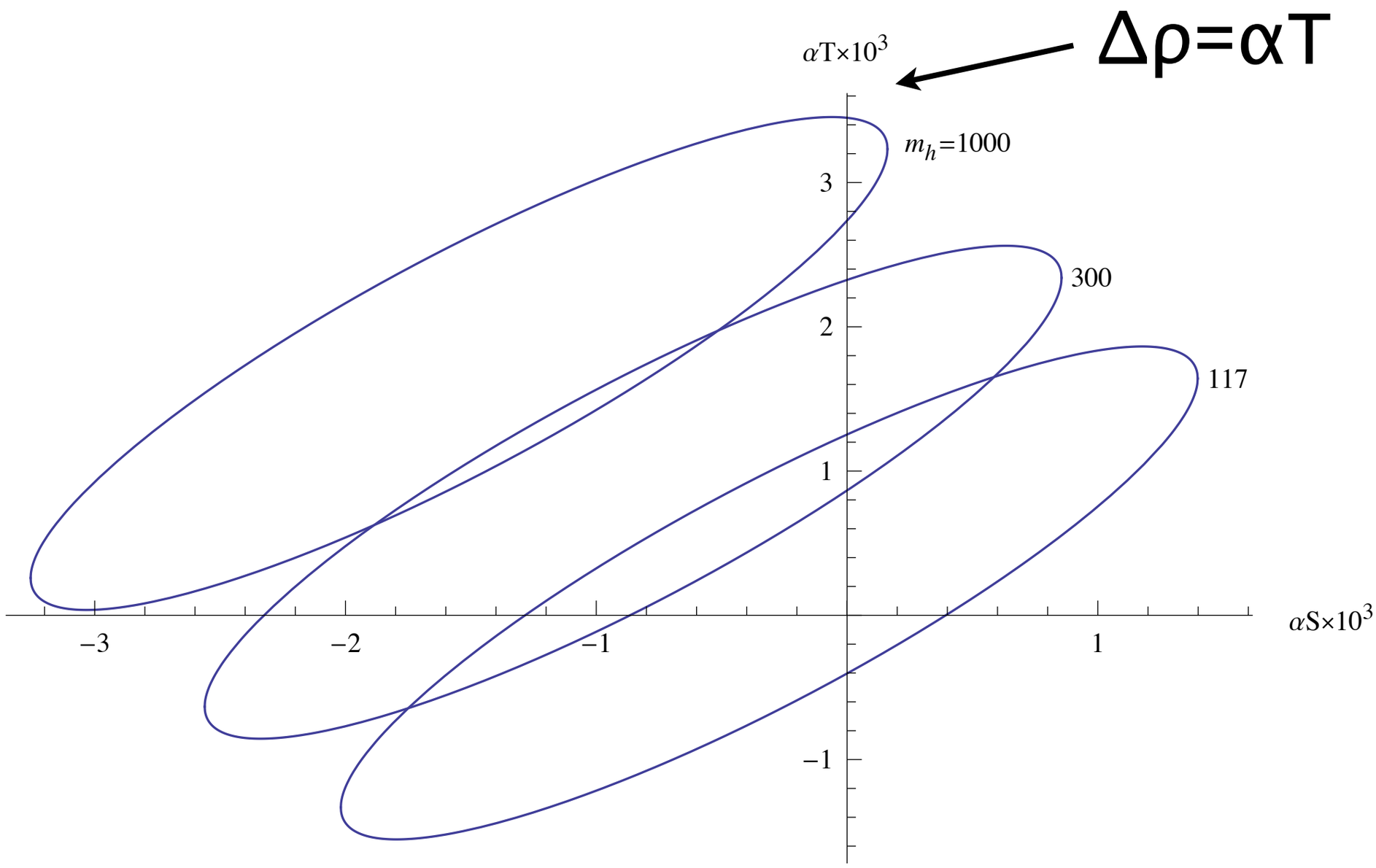


Data strongly disfavors large positive δg_{Lb}

(-2.8% g_{Lb} deviation shown)

LEP/SLD Final, Phys. Rep. 427 (2006) 257

LEP/SLD Data

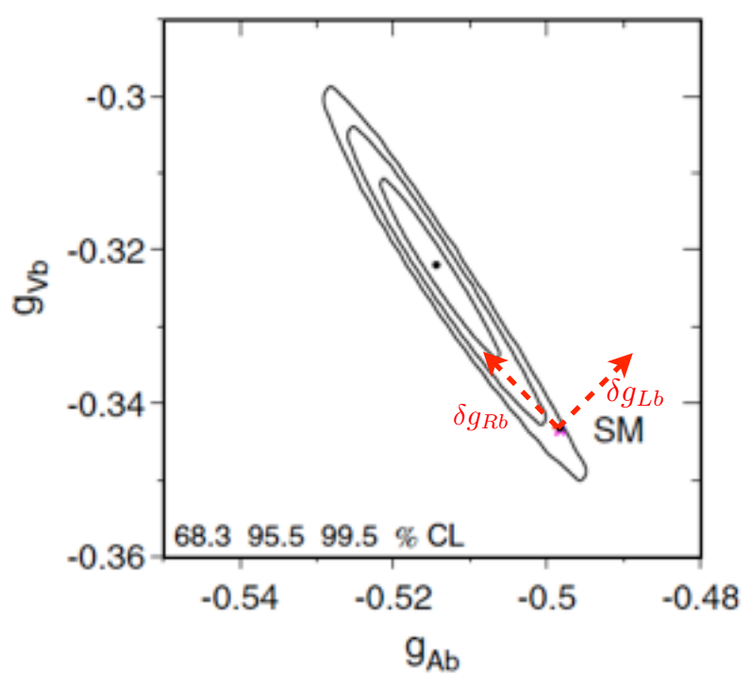


LEP/SLD Final, Phys. Rep. 427 (2006) 257

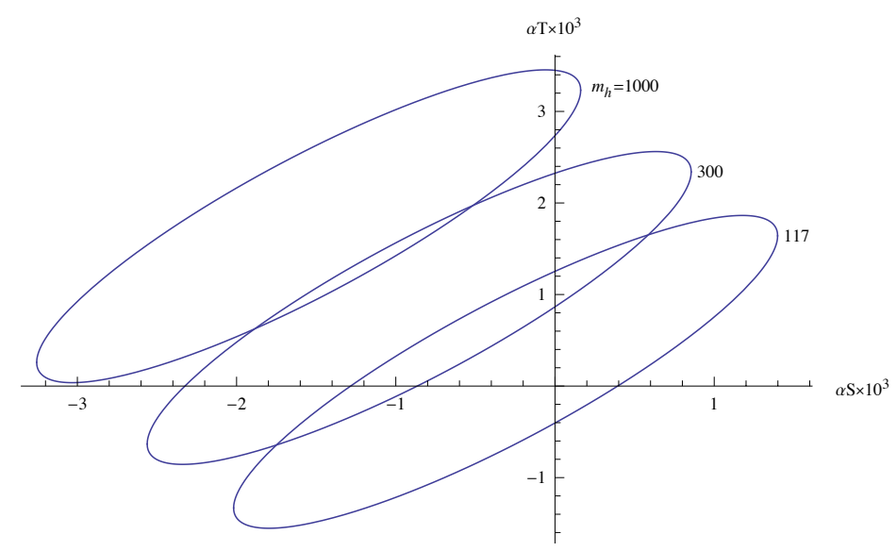
C. Amsler et. al. (PDG), Phys. Lett. B 667 (2008) 1

Can Custodial Symmetry be enhanced in a BSM top-mass sector?

$Z \to b\bar{b}$



$\Delta\rho$



A Custodial Symmetry for $Zb\bar{b}$

- $SU(2)_L x SU(2)_R x P_{LR} \rightarrow SU(2)_V x P_{LR}$ symmetry
- $(t_L,b_L)\in(2,2)$ - add new fermions
- $t_R\in(1,1)$ [or $(1,3)+(3,1)$]
- <u>Z-coupling: T_{3L}-$Q\sin^2\theta$</u>
  - Q unrenormalized ($\delta T_{3L}\neq 0$ in SM)
  - $\delta T_{3V}=\delta T_{3L}+\delta T_{3R}=0$, due to $SU(2)_V$
  - $\delta T_{3L}=\delta T_{3R}$ due to P_{LR}
    - hence $\delta T_{3L}=0$!

Agashe, et. al. PLB 641 (2006) 62

A Simple Realization: The Doublet-Extended Standard Model

- Global Symmetries:

$$SU(2)_L \times SU(2)_R \times P_{LR} \times U(1)_X$$
$$\rightarrow SU(2)_V \times P_{LR} \times U(1)_X$$

- Gauge Symmetries:

$$SU(2)_L \times U(1)_Y \rightarrow U(1)_Q$$
$$Y = T_{3R} + Q_X$$
$$Q = T_{3L} + T_{3R} + Q_X$$

- Fermions: $\mathcal{Q}_L = \begin{pmatrix} t'_L & \Omega_L \\ b_L & T'_L \end{pmatrix} = \begin{pmatrix} q_L & \Psi_L \end{pmatrix} \;\; \& \;\; t_R\,,\; \Omega_R\,,\; T'_R$

RSC, Simmons, Di Chiara, Foadi, PRD 80 (2009) 095001

New Symmetries

$$\mathcal{Q}_L = \overset{SU(2)_L}{\updownarrow}\overset{SU(2)_R}{\begin{pmatrix} t'_L & \Omega_L \\ b_L & T'_L \end{pmatrix}} \to L\mathcal{Q}_L R^\dagger$$

$$P_{LR}\mathcal{Q}_L = -\left[(i\sigma_2)\,\mathcal{Q}_L\,(i\sigma_2)\right]^T = \begin{pmatrix} T'_L & -\Omega_L \\ -b_L & t'_L \end{pmatrix}$$

Higgs:

$$\begin{aligned} \Phi &= \frac{1}{\sqrt{2}}\begin{pmatrix} v+h+i\phi^0 & i\sqrt{2}\,\phi^+ \\ i\sqrt{2}\,\phi^- & v+h-i\phi^0 \end{pmatrix} \\ &\to -[(i\sigma_2)\Phi(i\sigma_2)]^T \end{aligned}$$

Fermion Charges

	t'_L	b_L	Ω_L	T'_L	t'_R	b_R	Ω_R	T'_R
T^3_L	$\frac{1}{2}$	$-\frac{1}{2}$	$\frac{1}{2}$	$-\frac{1}{2}$	0	0	$\frac{1}{2}$	$-\frac{1}{2}$
T^3_R	$-\frac{1}{2}$	$-\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	0	-1	0	0
Q	$\frac{2}{3}$	$-\frac{1}{3}$	$\frac{5}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	$-\frac{1}{3}$	$\frac{5}{3}$	$\frac{2}{3}$
Y	$\frac{1}{6}$	$\frac{1}{6}$	$\frac{7}{6}$	$\frac{7}{6}$	$\frac{2}{3}$	$-\frac{1}{3}$	$\frac{7}{6}$	$\frac{7}{6}$
Q_X	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{7}{6}$	$\frac{7}{6}$

- t'_L & T'_L have charge of top-quark (will mix)
- Ω_L exotic (unstable) quark with charge +5/3
- $\Psi_{L,R}$ vectorial under weak interactions

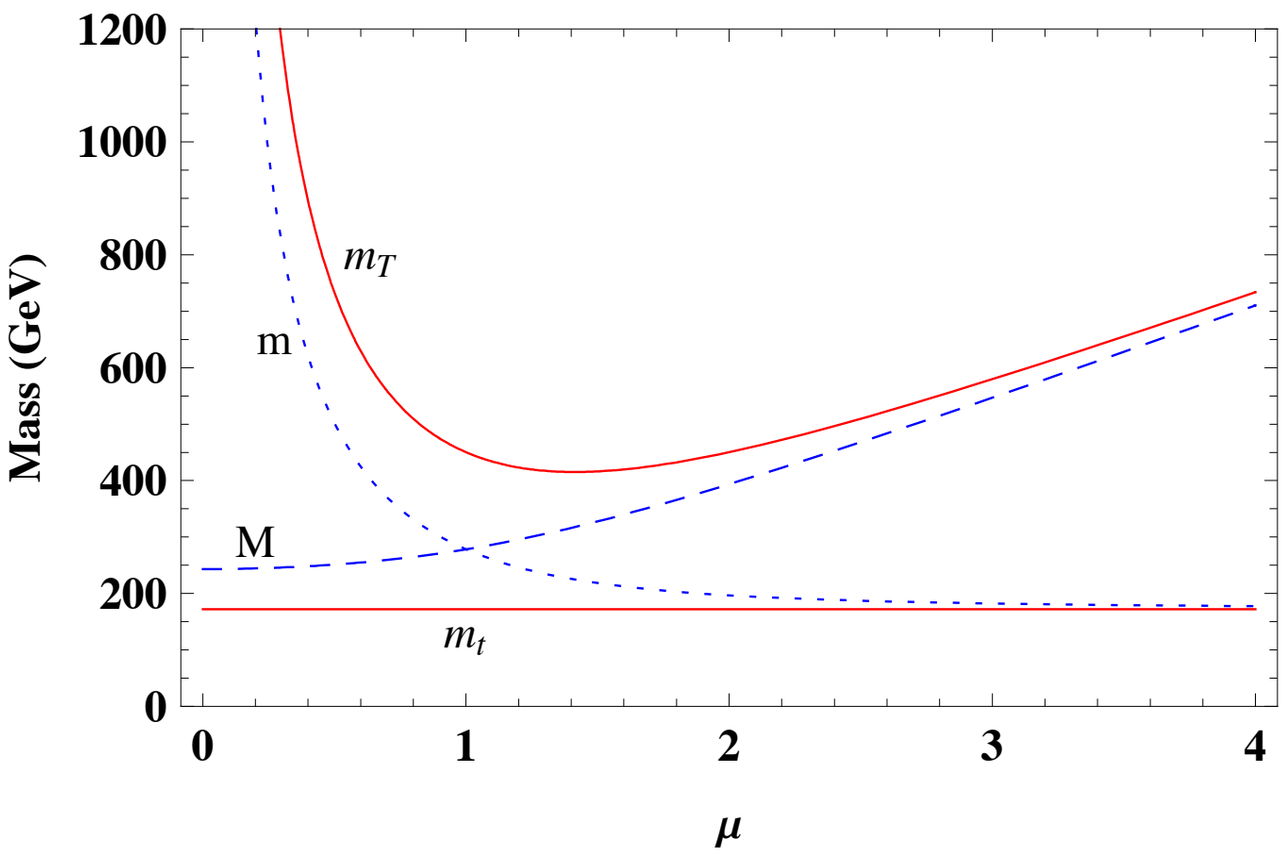
Lagrangian

$$\begin{aligned}\mathcal{L}_{fermion} &= \mathrm{Tr}\bar{\mathcal{Q}}_L i\not{D}\mathcal{Q}_L + \bar{\Psi} i\not{D}\Psi + \bar{t}'_R i\not{D} t'_R \\ &\quad -\lambda_r \left(\mathrm{Tr}\bar{\mathcal{Q}}_L \cdot \Phi\right) t'_r - M\bar{\Psi}_L\Psi_R + h.c.\end{aligned}$$

- $SU(2)_L x SU(2)_R x P_{LR}$ exact at dimension 4 in top-quark mass-generating sector
- *Softly broken* by Ψ mass to gauged $SU(2)_L x U(1)_Y$
- Explicitly broken by (small) gauge-interactions
- Ordinary Higgs Lagrangian
- $m_b=0$, $m_\Omega=M$

Top Mass Eigenstates

$$\mathcal{L}_{\rm mass} = -\begin{pmatrix} t'_L & T'_L \end{pmatrix} \begin{pmatrix} m & 0 \\ m & M \end{pmatrix} \begin{pmatrix} t'_R \\ T'_R \end{pmatrix} - M\bar{\Omega}_L\Omega_R + \text{h.c} \quad , \qquad m = \frac{\lambda_t v}{\sqrt{2}}$$

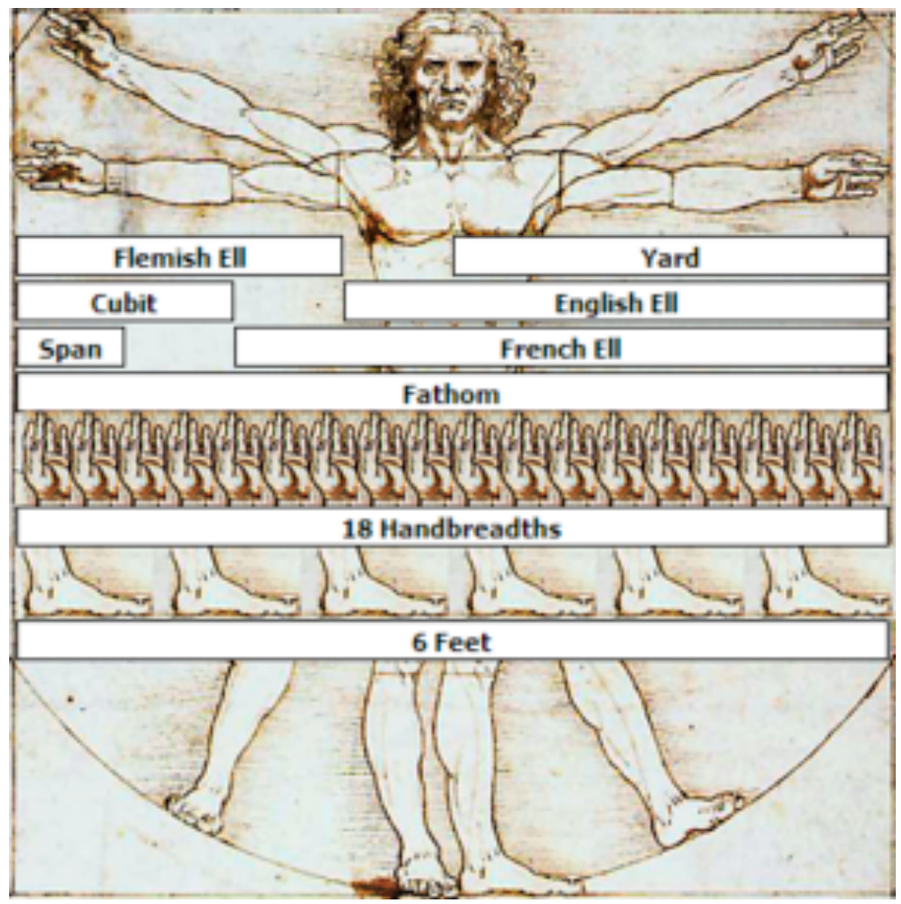


m_t fixed

$\mu = M/m$

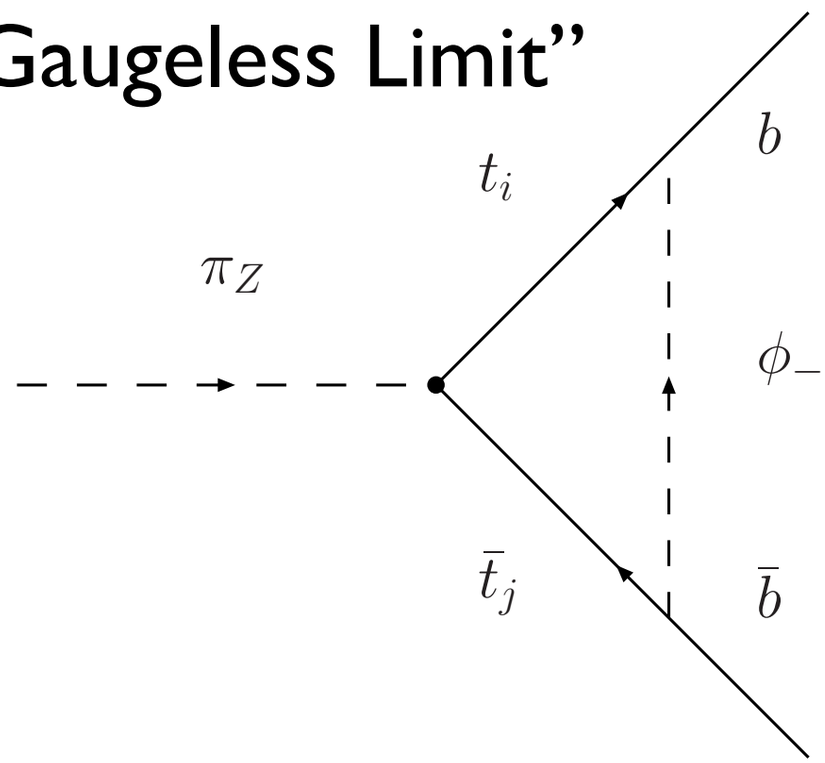
- $\mu \to \infty$, SM limit
- $\mu \to 0$, custodial limit (NB: λ_t large for fixed m_t)

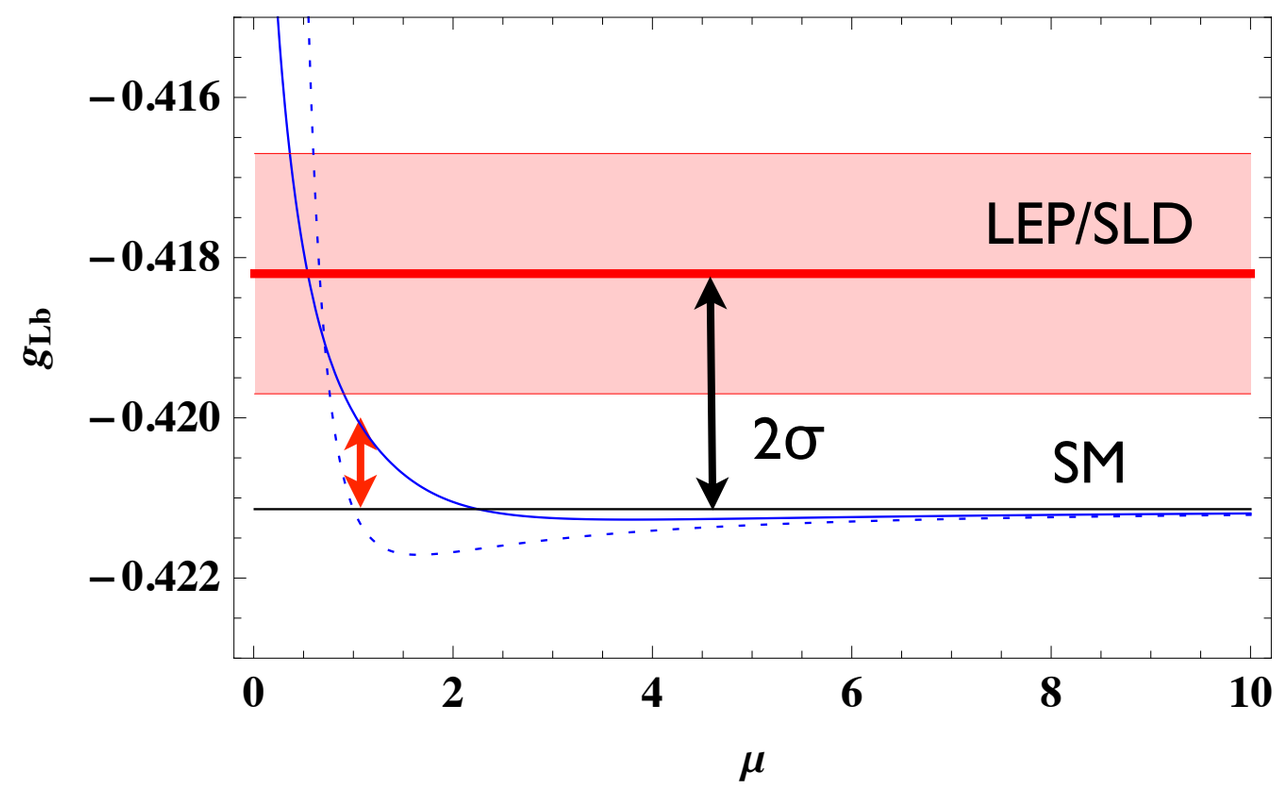
Constraints on the DESM



$Zb\bar{b}$ in DESM

"Gaugeless Limit"



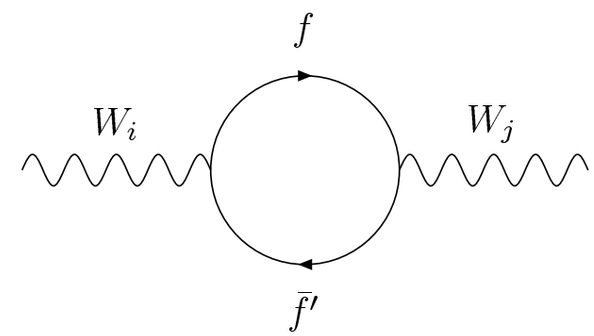


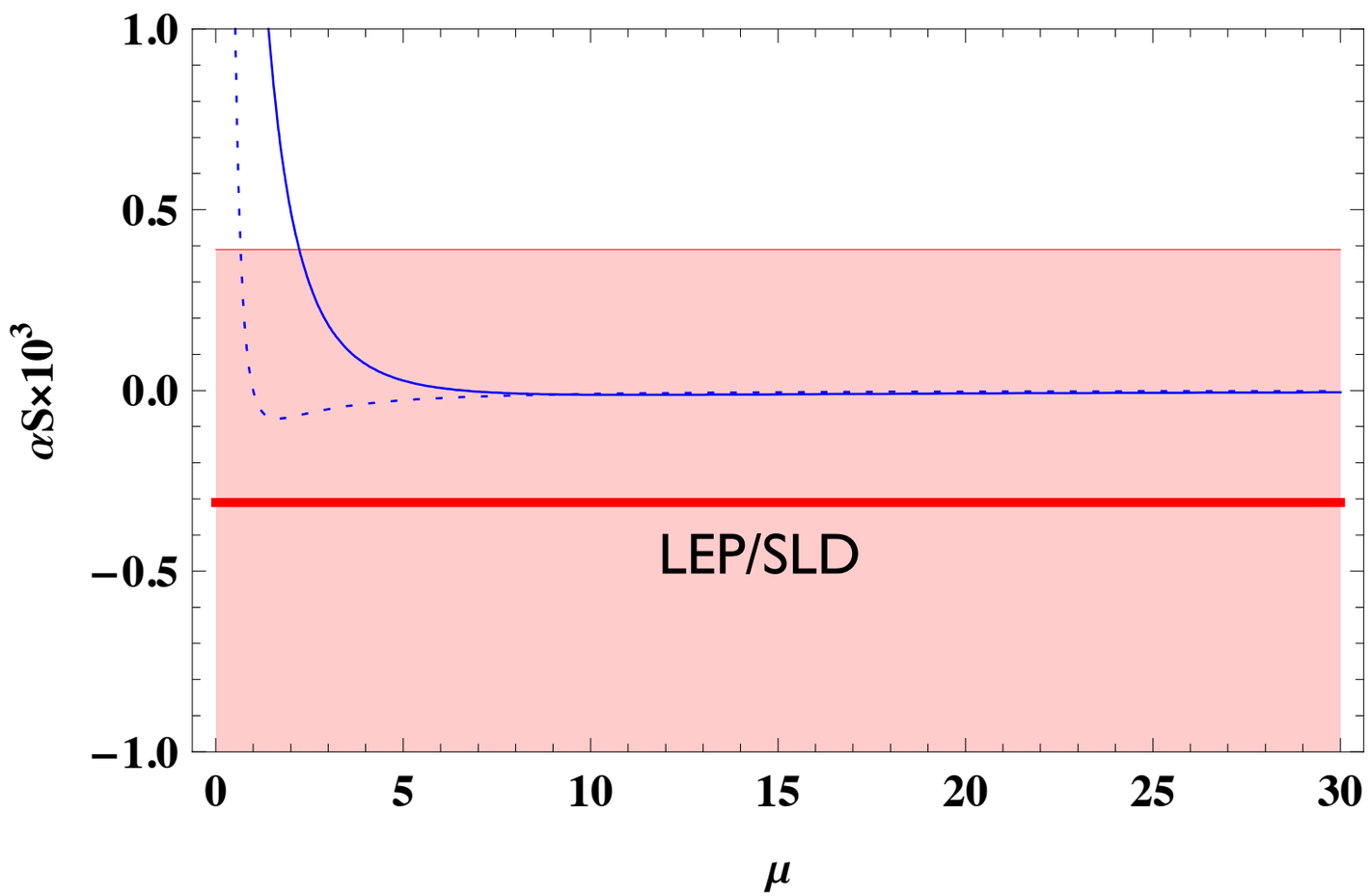
Negative contribution for small μ: Custodial symmetry restoration!

Favors small μ

αS in DESM

$$\alpha S = 16\pi\alpha \left[\frac{d}{dq}\Pi_{33}(0) - \frac{d}{dq}\Pi_{3Q}(0) \right]_{new\ physics}$$



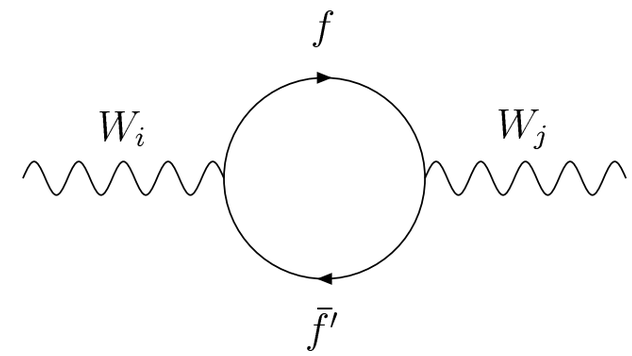


SM (m_h=115 GeV)

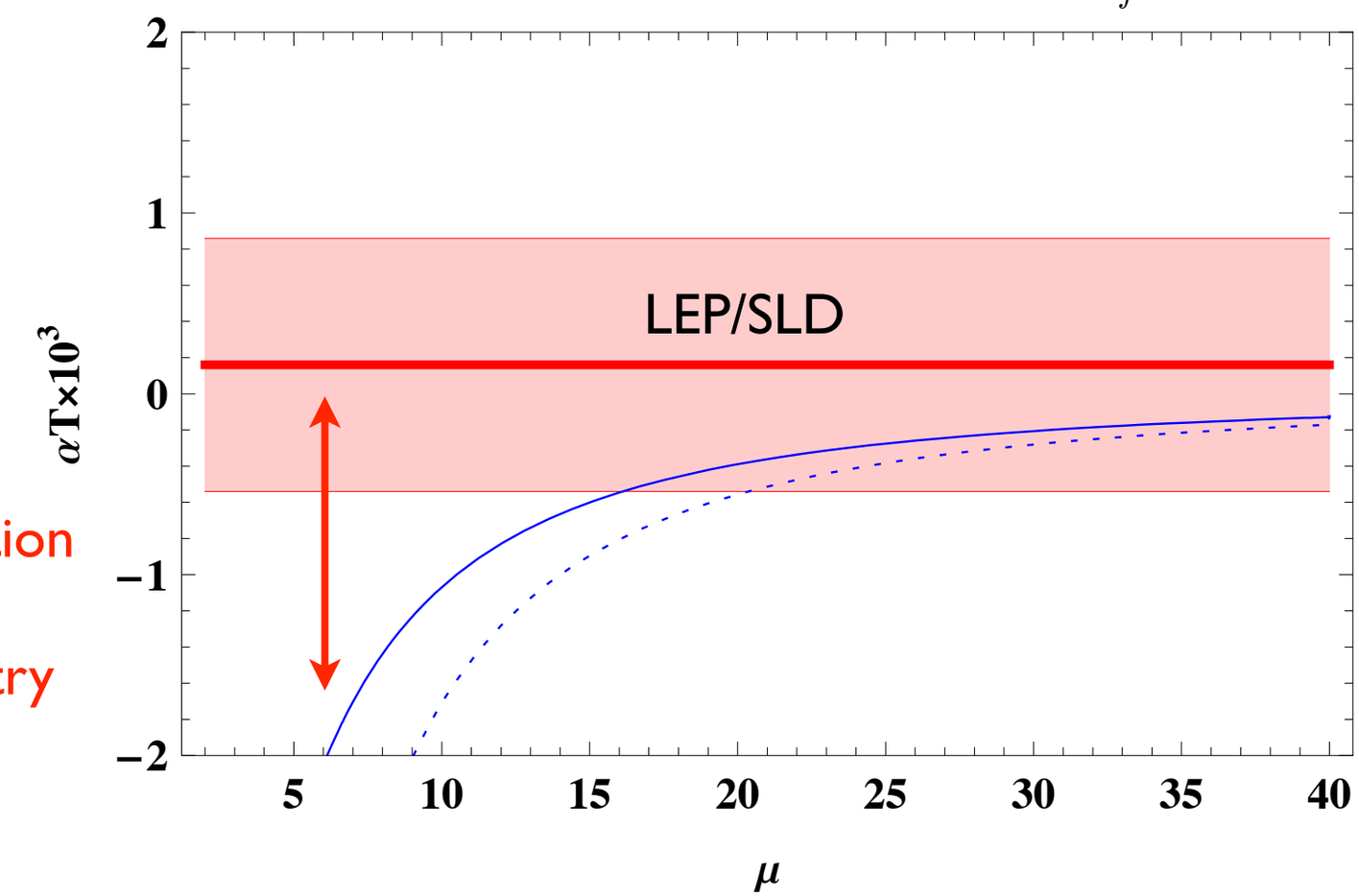
(μ > few slightly favored)

αT in DESM

$$\alpha T = \left[\frac{\Pi_{WW}(0)}{M_W^2} - \frac{\Pi_{ZZ}(0)}{M_Z^2}\right]_{new\ physics}$$



Negative contribution for small μ: Custodial symmetry restoration!



SM (m_h=115 GeV)

Large μ strongly favored!

m_T>3.4 TeV @ 95% CL

"Broken Symmetry", Wilson

Experiment strongly favors custodial symmetry breaking *no smaller than* that due to top-quark in SM!

Conclusions and Questions

- Little room for enhanced custodial symmetry
- Potential, however, to use enhanced custodial symmetry in "heavy" sector of theory, to control extra contributions to αT
- Can we implement this in a dynamical model?
  - Embed $SU(2)_R$ in ETC?
- What about flavor mixing?