Electroweak Constraints on New Particles

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Corfú 2010

Outline

Jorge de Blas' PhD Thesis
arXiv:0803.4008 [hep-ph]
arXiv:1005.3998 [hep-ph]

- Introduction
- Model Independent Limits
- Constraints on General Extra Leptons
- Constraints on General Extra Vectors
- Implications on the Higgs mass
- Several New Particles
- Conclusions

New Physics @ LHC

- BSM: many models + *unexpected*
- At any rate, new particles !

Present constraints on masses and couplings:
Flavour, Tevatron, EW Precision Tests

Searches ↙ ↘ Discovery ☺

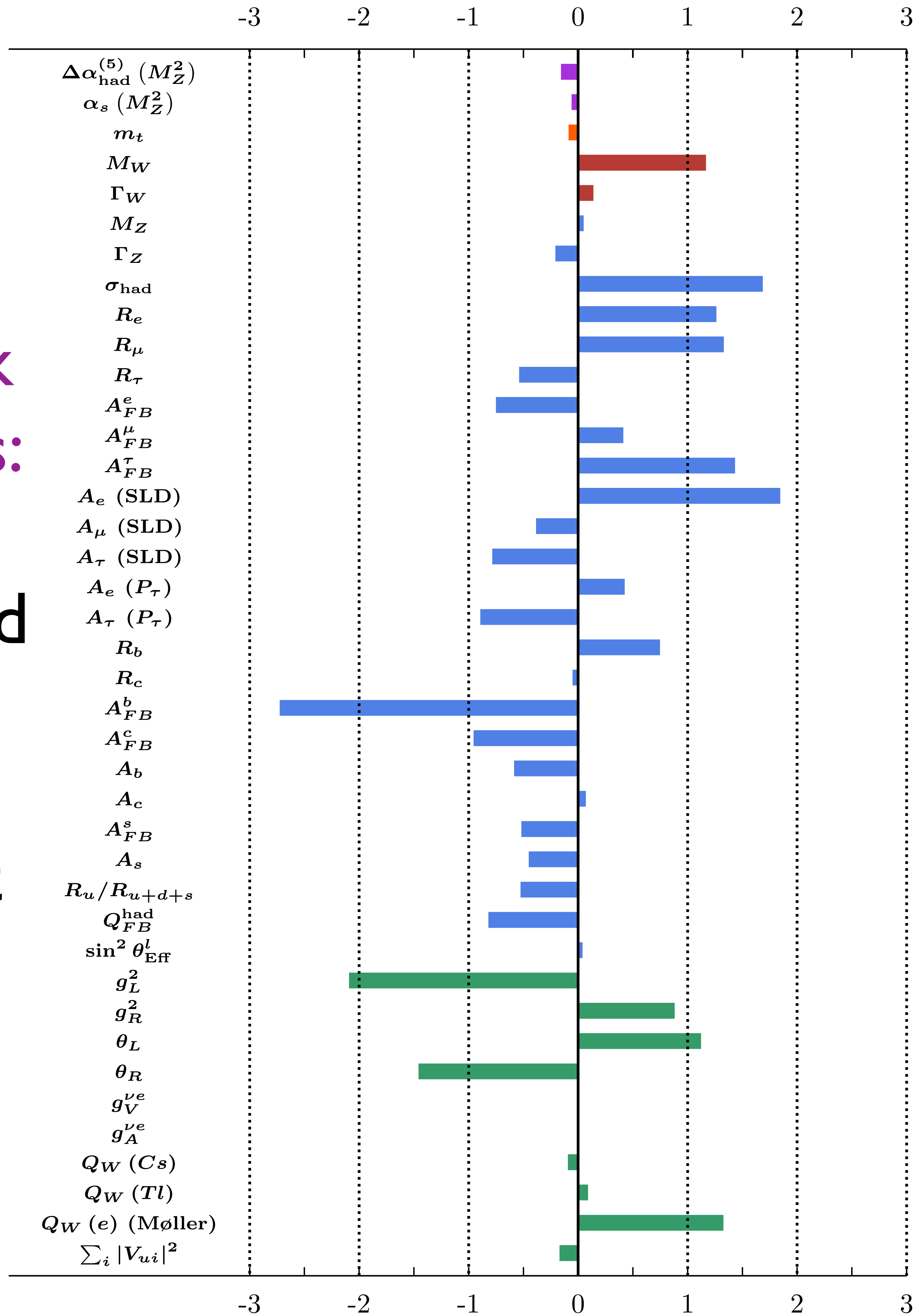
Restrict parameter space | Check consistency

Electroweak Precision Data

- Z-pole observables: mass, partial decay widths, left-right and forward-backward asymmetries
- W properties: mass, width, leptonic branching ratios
- Muon decay
- Low-energy neutrino scattering: neutrino-nucleon DIS and neutrino-electron scattering
- Parity violation in atoms and in Møller scattering.
- Unitarity constraints on CKM (1st row)
- Fermion pair production off Z-pole at LEP 2

Precision Electroweak Observables:

The Standard Model vs Experiment



Good agreement in general

Effective Description of BSM

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_4 + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \ldots$$

SM

Scale of New Physics

Suppressed at low energies

$$\mathcal{L}_d = \sum_{i=1}^{N_d} \alpha_i^{[d]} \mathcal{O}_i^{[d]}$$

Gauge-invariant operators built with SM fields

Dimensionless coefficients

Unique Operator of dimension 5 (lepton number violating)

Operators of dimension 6

	Operator	Notation	Operator	Notation
	$\overline{l_L^c}\tilde{\phi}^*\tilde{\phi}^\dagger l_L$	$\mathcal{O}_5$		
LLLL	$\frac{1}{2}\left(\overline{l_L}\gamma_\mu l_L\right)\left(\overline{l_L}\gamma^\mu l_L\right)$	$\mathcal{O}_{ll}^{(1)}$	$\frac{1}{2}\left(\overline{l_L}\gamma_\mu\sigma_a l_L\right)\left(\overline{l_L}\gamma^\mu\sigma_a l_L\right)$	$\mathcal{O}_{ll}^{(3)}$
	$\frac{1}{2}\left(\overline{q_L}\gamma_\mu q_L\right)\left(\overline{q_L}\gamma^\mu q_L\right)$	$\mathcal{O}_{qq}^{(1,1)}$	$\frac{1}{2}\left(\overline{q_L}\gamma_\mu\sigma_a q_L\right)\left(\overline{q_L}\gamma^\mu\sigma_a q_L\right)$	$\mathcal{O}_{qq}^{(1,3)}$
	$\left(\overline{l_L}\gamma_\mu l_L\right)\left(\overline{q_L}\gamma^\mu q_L\right)$	$\mathcal{O}_{lq}^{(1)}$	$\left(\overline{l_L}\gamma_\mu\sigma_a l_L\right)\left(\overline{q_L}\gamma^\mu\sigma_a q_L\right)$	$\mathcal{O}_{lq}^{(3)}$
	$\frac{1}{2}\left(\overline{q_L}\gamma_\mu\lambda_A q_L\right)\left(\overline{q_L}\gamma^\mu\lambda_A q_L\right)$	$\mathcal{O}_{qq}^{(8,1)}$	$\frac{1}{2}\left(\overline{q_L}\gamma_\mu\sigma_a\lambda_A q_L\right)\left(\overline{q_L}\gamma^\mu\sigma_a\lambda_A q_L\right)$	$\mathcal{O}_{qq}^{(8,3)}$
RRRR			$\frac{1}{2}\left(\overline{e_R}\gamma_\mu e_R\right)\left(\overline{e_R}\gamma^\mu e_R\right)$	$\mathcal{O}_{ee}$
	$\frac{1}{2}\left(\overline{u_R}\gamma_\mu u_R\right)\left(\overline{u_R}\gamma^\mu u_R\right)$	$\mathcal{O}_{uu}^{(1)}$	$\frac{1}{2}\left(\overline{d_R}\gamma_\mu d_R\right)\left(\overline{d_R}\gamma^\mu d_R\right)$	$\mathcal{O}_{dd}^{(1)}$
	$\left(\overline{e_R}\gamma_\mu e_R\right)\left(\overline{u_R}\gamma^\mu u_R\right)$	$\mathcal{O}_{eu}$	$\left(\overline{e_R}\gamma_\mu e_R\right)\left(\overline{d_R}\gamma^\mu d_R\right)$	$\mathcal{O}_{ed}$
	$\left(\overline{u_R}\gamma_\mu u_R\right)\left(\overline{d_R}\gamma^\mu d_R\right)$	$\mathcal{O}_{ud}^{(1)}$		
	$\frac{1}{2}\left(\overline{u_R}\gamma_\mu\lambda_A u_R\right)\left(\overline{u_R}\gamma^\mu\lambda_A u_R\right)$	$\mathcal{O}_{uu}^{(8)}$	$\frac{1}{2}\left(\overline{d_R}\gamma_\mu\lambda_A d_R\right)\left(\overline{d_R}\gamma^\mu\lambda_A d_R\right)$	$\mathcal{O}_{dd}^{(8)}$
	$\left(\overline{u_R}\gamma_\mu\lambda_A u_R\right)\left(\overline{d_R}\gamma^\mu\lambda_A d_R\right)$	$\mathcal{O}_{ud}^{(8)}$		
LRRL	$\left(\overline{l_L}e_R\right)\left(\overline{e_R}l_L\right)$	$\mathcal{O}_{le}$	$\left(\overline{q_L}e_R\right)\left(\overline{e_R}q_L\right)$	$\mathcal{O}_{qe}$
	$\left(\overline{l_L}u_R\right)\left(\overline{u_R}l_L\right)$	$\mathcal{O}_{lu}$	$\left(\overline{l_L}d_R\right)\left(\overline{d_R}l_L\right)$	$\mathcal{O}_{ld}$
	$\left(\overline{q_L}u_R\right)\left(\overline{u_R}q_L\right)$	$\mathcal{O}_{qu}^{(1)}$	$\left(\overline{q_L}d_R\right)\left(\overline{d_R}q_L\right)$	$\mathcal{O}_{qd}^{(1)}$
	$\left(\overline{l_L}e_R\right)\left(\overline{d_R}q_L\right)$	$\mathcal{O}_{qde}$		
	$\left(\overline{q_L}\lambda_A u_R\right)\left(\overline{u_R}\lambda_A q_L\right)$	$\mathcal{O}_{qu}^{(8)}$	$\left(\overline{q_L}\lambda_A d_R\right)\left(\overline{d_R}\lambda_A q_L\right)$	$\mathcal{O}_{qd}^{(8)}$
	$\epsilon_{ABC}(\overline{l_L}i\sigma_2 q_L^{c\ A})(\overline{d_R^B}u_R^{c\ C})$	$\mathcal{O}_{lqdu}$	$\epsilon_{ABC}(\overline{q_L^B}i\sigma_2 q_L^{c\ C})(\overline{e_R}u_R^{c\ A})$	$\mathcal{O}_{qqeu}$
	$\epsilon_{ABC}(\overline{u_R^A}u_R^{c\ B})(\overline{d_R^C}e_R^c)$	$\mathcal{O}_{uude}$		
LRLR	$\left(\overline{q_L}u_R\right)i\sigma_2\left(\overline{q_L}d_R\right)$	$\mathcal{O}_{qq}^{(1)}$	$\left(\overline{q_L}\lambda_A u_R\right)i\sigma_2\left(\overline{q_L}\lambda_A d_R\right)$	$\mathcal{O}_{qq}^{(8)}$
	$\left(\overline{l_L}e_R\right)i\sigma_2\left(\overline{q_L}u_R\right)$	$\mathcal{O}_{lq}$	$\left(\overline{l_L}u_R\right)i\sigma_2\left(\overline{q_L}e_R\right)$	$\mathcal{O}_{lq'}$
	$\epsilon_{ABC}(\overline{l_L}i\sigma_2 q_L^{c\ A})(\overline{q_L^B}i\sigma_2 q_L^{c\ C})$	$\mathcal{O}_{qqql}$	$\epsilon_{ABC}(\overline{u_R^{c\ A}}d_R^B)(\overline{u_R^{c\ C}}e_R)$	$\mathcal{O}_{udue}$
	$\left(\phi^\dagger\phi\right)^2$	$\mathcal{O}_{\phi 4}$	$\frac{1}{3}\left(\phi^\dagger\phi\right)^3$	$\mathcal{O}_{\phi 6}$
SVF	$\left(\phi^\dagger iD_\mu\phi\right)\left(\overline{l_L}\gamma^\mu l_L\right)$	$\mathcal{O}_{\phi l}^{(1)}$	$\left(\phi^\dagger\sigma_a iD_\mu\phi\right)\left(\overline{l_L}\gamma^\mu\sigma_a l_L\right)$	$\mathcal{O}_{\phi l}^{(3)}$
	$\left(\phi^\dagger iD_\mu\phi\right)\left(\overline{e_R}\gamma^\mu e_R\right)$	$\mathcal{O}_{\phi e}^{(1)}$		
	$\left(\phi^\dagger iD_\mu\phi\right)\left(\overline{q_L}\gamma^\mu q_L\right)$	$\mathcal{O}_{\phi q}^{(1)}$	$\left(\phi^\dagger\sigma_a iD_\mu\phi\right)\left(\overline{q_L}\gamma^\mu\sigma_a q_L\right)$	$\mathcal{O}_{\phi q}^{(3)}$
	$\left(\phi^\dagger iD_\mu\phi\right)\left(\overline{u_R}\gamma^\mu u_R\right)$	$\mathcal{O}_{\phi u}^{(1)}$	$\left(\phi^\dagger iD_\mu\phi\right)\left(\overline{d_R}\gamma^\mu d_R\right)$	$\mathcal{O}_{\phi d}^{(1)}$
	$\left(\phi^T i\sigma_2 iD_\mu\phi\right)\left(\overline{u_R}\gamma^\mu d_R\right)$	$\mathcal{O}_{\phi ud}$		
SF	$\left(\phi^\dagger\phi\right)\left(\overline{l_L}\,\phi\,e_R\right)$	$\mathcal{O}_{e\phi}$		
	$\left(\phi^\dagger\phi\right)\left(\overline{q_L}\,\tilde{\phi}\,u_R\right)$	$\mathcal{O}_{u\phi}$	$\left(\phi^\dagger\phi\right)\left(\overline{q_L}\,\phi\,d_R\right)$	$\mathcal{O}_{d\phi}$
Oblique	$\phi^\dagger\phi\left(D^\mu\phi\right)^\dagger D_\mu\phi$	$\mathcal{O}_{\phi}^{(1)}$	$\left(\phi^\dagger D_\mu\phi\right)\left(\left(D^\mu\phi\right)^\dagger\phi\right)$	$\mathcal{O}_{\phi}^{(3)}$
	$\phi^\dagger\sigma_a\phi\,W_{\mu\nu}^a B^{\mu\nu}$	$\mathcal{O}_{WB}$		

EW limits on coefficients

	Operator coefficient	Z pole	W data	Low Energy	LEP 2	Global fit
				95% C.L. limits $[\mathrm{TeV}^{-2}]$		
LLLL	$\frac{\alpha_{ll}^{(1)}}{\Lambda^2}$	-	-	$[-0.033, 0.245]$	$[-0.089, 0.024]$	$[-0.065, 0.040]$
	$\frac{\alpha_{ll}^{(3)}}{\Lambda^2}$	$[-0.010, 0.012]$	$[-0.007, 0.009]$	$[-0.088, -0.007]$	$[-0.046, 0.041]$	$[-0.007, 0.006]$
	$\frac{\alpha_{lq}^{(1)}}{\Lambda^2}$	-	-	$[-0.027, 0.020]$	$[-0.007, 0.433]$	$[-0.024, 0.022]$
	$\frac{\alpha_{lq}^{(3)}}{\Lambda^2}$	-	$[-0.007, 0.009]$	$[-0.003, 0.090]$	$[-6{\cdot}10^{-4}, 0.056]$	$[-0.003, 0.012]$
RRRR	$\frac{\alpha_{ee}}{\Lambda^2}$	-	-	$[-0.257, 0.031]$	$[-0.057, 0.011]$	$[-0.060, 0.006]$
	$\frac{\alpha_{eu}}{\Lambda^2}$	-	-	$[-0.040, 0.057]$	$[-0.195, 0.001]$	$[-0.057, 0.030]$
	$\frac{\alpha_{ed}}{\Lambda^2}$	-	-	$[-0.041, 0.048]$	$[-0.002, 0.260]$	$[-0.025, 0.059]$
LRRL	$\frac{\alpha_{le}}{\Lambda^2}$	-	-	$[-1.146, 1.132]$	$[-0.059, 0.101]$	$[-0.059, 0.101]$
	$\frac{\alpha_{lu}}{\Lambda^2}$	-	-	$[-0.090, 0.100]$	$[-0.005, 0.947]$	$[-0.070, 0.116]$
	$\frac{\alpha_{ld}}{\Lambda^2}$	-	-	$[-0.078, 0.098]$	$[-1.263, 0.007]$	$[-0.089, 0.085]$
	$\frac{\alpha_{qe}}{\Lambda^2}$	-	-	$[-0.052, 0.041]$	$[-0.006, 0.561]$	$[-0.044, 0.048]$
SVF	$\frac{\alpha_{\phi l}^{(1)}}{\Lambda^2}$	$[-0.004, 0.009]$	-	$[-0.023, 0.072]$	$[-0.037, 0.170]$	$[-0.003, 0.010]$
	$\frac{\alpha_{\phi q}^{(1)}}{\Lambda^2}$	$[-0.021, 0.033]$	-	$[-0.025, 0.023]$	$[-0.014, 1.149]$	$[-0.013, 0.022]$
	$\frac{\alpha_{\phi e}^{(1)}}{\Lambda^2}$	$[-0.011, 0.006]$	-	$[-0.147, 0.053]$	$[-0.233, 0.103]$	$[-0.012, 0.006]$
	$\frac{\alpha_{\phi u}^{(1)}}{\Lambda^2}$	$[-0.054, 0.066]$	-	$[-0.035, 0.060]$	$[-0.076, 2.796]$	$[-0.026, 0.048]$
	$\frac{\alpha_{\phi d}^{(1)}}{\Lambda^2}$	$[-0.130, 0.032]$	-	$[-0.060, 0.046]$	$[-3.727, 0.101]$	$[-0.049, 0.028]$
	$\frac{\alpha_{\phi l}^{(3)}}{\Lambda^2}$	$[-0.007, 0.006]$	$[-0.009, 0.006]$	$[\ 0.010, 0.068]$	$[-0.151, 0.008]$	$[-0.005, 0.004]$
	$\frac{\alpha_{\phi q}^{(3)}}{\Lambda^2}$	$[-0.008, 0.011]$	$[-0.009, 0.007]$	$[-0.090, -0.003]$	$[-0.002, 0.305]$	$[-0.007, 0.006]$
	$\frac{\alpha_{\phi ud}}{\Lambda^2}$	-	$[-0.015, 0.018]$	$[-0.006, 0.208]$	-	$[-0.012, 0.020]$
Oblique	$\frac{\alpha_{\phi}^{(3)}}{\Lambda^2}$	$[-0.031, 0.019]$	$[-0.041, 0.003]$	$[0.024, 0.174]$	$[-0.344, 0.033]$	$[-0.031, 0.008]$
	$\frac{\alpha_{WB}}{\Lambda^2}$	$[-0.006, 0.006]$	$[-0.019, 0.001]$	$[0.007, 0.068]$	$[-0.155, 0.017]$	$[-0.006, 0.004]$

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	$\frac{\alpha_{ll}^{(3)}}{\Lambda^2}$	$[-0.010, 0.012]$	$[-0.007, 0.009]$	$[-0.088, -0.007]$	$[-0.046, 0.041]$	$[-0.007, 0.006]$
	$\frac{\alpha_{lq}^{(1)}}{\Lambda^2}$	-	-	$[-0.027, 0.020]$	$[-0.007, 0.433]$	$[-0.024, 0.022]$
	$\frac{\alpha_{lq}^{(3)}}{\Lambda^2}$	-	$[-0.007, 0.009]$	$[-0.003, 0.090]$	$[-6{\cdot}10^{-4}, 0.056]$	$[-0.003, 0.012]$
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SVF	$\frac{\alpha_{\phi l}^{(1)}}{\Lambda^2}$	$[-0.004, 0.009]$	-	$[-0.023, 0.072]$	$[-0.037, 0.170]$	$[-0.003, 0.010]$
	$\frac{\alpha_{\phi q}^{(1)}}{\Lambda^2}$	$[-0.021, 0.033]$	-	$[-0.025, 0.023]$	$[-0.014, 1.149]$	$[-0.013, 0.022]$
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Problems

- Ignores relations among coefficients
- No clear lessons about New Physics or direct relation with Specific Models
- No direct connection to Collider Searches

We would like to be more specific but retain, as far as possible, model independence

“Particle” approach

Explore all possible extensions of the SM with new particles (fields) that can give observable contributions

- Need to be systematic
- Need sensible assumptions
- Direct connection to particle searches
- Simple relation to Models

General Extensions of the SM

Impose Symmetries! → • Classify particles
→ • Restrict interactions

Lorentz Invariance ⇒ Scalars, Spinors, Vectors

SU(3)xSU(2)xU(1) Gauge Invariance ⇒ EW singlets, doublets, triplets; Hypercharged; Coloured

Condition: *Sizable effects*

- New Physics enters at Tree Level

  (Theories with R-, T-, KK-... parity not studied here)

- Renormalizable Interactions

+ Symmetries

It is possible to write a general Lagrangian

General Extra Leptons

- Spin $\frac{1}{2}$ uncoloured particles
- Vectorlike
- GUT, Xdims, seesaw
- Contribute to EWPT via mixing with SM leptons, induced by Yukawa couplings

flavour structure not explicit

$$\mathcal{L} \supset \sum_L \left\{ \eta_L \left(\bar{L} \not{D} L - M_L \bar{L} L \right) - y_{Le} \overline{L_L} \Phi_{Le} e - y_{Ll} \overline{L_R} \Phi_{Ll} l \right\} + \text{h.c.}$$

All Types of Extra Leptons

Leptons	N	E	$\begin{pmatrix} N \\ E^- \end{pmatrix}$	$\begin{pmatrix} E^- \\ E^{--} \end{pmatrix}$	$\begin{pmatrix} E^+ \\ N \\ E^- \end{pmatrix}$	$\begin{pmatrix} N \\ E^- \\ E^{--} \end{pmatrix}$
Notation			Δ_1	Δ_3	Σ_0	Σ_1
$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$	$(1,1)_0$	$(1,1)_{-1}$	$(1,2)_{-\frac{1}{2}}$	$(1,2)_{-\frac{3}{2}}$	$(1,3)_0$	$(1,3)_{-1}$
Spinor	Dirac or Majorana	Dirac	Dirac	Dirac	Dirac or Majorana	Dirac

Seesaw Messengers {
Type I → singlet N
Type III → triplet Σ_0

Global Fits

Quality of the fit (compared to SM)

Coupling	$n_{\rm par}^{\rm new}$	$-\Delta\chi^2_{\rm min}$ $(\chi^2_{\rm min}/{\rm d.o.f.})$ N	E	Δ_1	Δ_3	Σ_0	Σ_1
General	3	1.2 (1.11)	0.2 (1.13)	1.7 (1.09)	1.7 (1.09)	1.1 (1.11)	0 (1.14)
Universal	1	0.2 (0.94)	0 (0.94)	0 (0.94)	0.4 (0.93)	0.5 (0.93)	0 (0.94)
Only with e	1	0.4 (1.07)	0 (1.08)	0 (1.08)	0.9 (1.06)	0.8 (1.06)	0 (1.08)
Only with μ	1	0.1 (1.08)	0.2 (1.08)	1.7 (1.04)	0 (1.08)	0 (1.08)	0 (1.08)
Only with τ	1	1 (1.06)	0 (1.08)	0 (1.08)	0.5 (1.07)	0.4 (1.07)	0 (1.08)

Marginal improvement at best

Constraints on Mixings $U \sim \frac{yv}{M}$

Coupling		N	E	Δ_1	Δ_3	Σ_0	Σ_1
Only with e	$\lvert U \rvert <$	0.051	0.020	0.020	0.028	0.020	0.016
	$\lvert U_{\rm min} \rvert =$	0.023	0	0	0.019	0.012	0
Only with μ	$\lvert U \rvert <$	0.031	0.029	0.048	0.028	0.018	0.024
	$\lvert U_{\rm min} \rvert =$	0.012	0.014	0.033	0	0	0.005
Only with τ	$\lvert U \rvert <$	0.087	0.033	0.035	0.045	0.030	0.029
	$\lvert U_{\rm min} \rvert =$	0.056	0	0	0.027	0.016	0
Universal	$\lvert U \rvert <$	0.028	0.019	0.020	0.025	0.017	0.013
	$\lvert U_{\rm min} \rvert =$	0.013	0	0	0.014	0.010	0

Constraints on Mixings $U \sim \frac{yv}{M}$

Coupling		N	E	Δ_1	Δ_3	Σ_0	Σ_1
Only with e	$\lvert U \rvert <$	0.051	0.020	0.020	0.028	0.020	0.016
	$\lvert U_{\rm min} \rvert =$	0.023	0	0	0.019	0.012	0
Only with μ	$\lvert U \rvert <$	0.031	0.029	0.048	0.028	0.018	0.024
	$\lvert U_{\rm min} \rvert =$	0.012	0.014	0.033	0	0	0.005
Only with τ	$\lvert U \rvert <$	0.087	0.033	0.035	0.045	0.030	0.029
	$\lvert U_{\rm min} \rvert =$	0.056	0	0	0.027	0.016	0
Universal	$\lvert U \rvert <$	0.028	0.019	0.020	0.025	0.017	0.013
	$\lvert U_{\rm min} \rvert =$	0.013	0	0	0.014	0.010	0

Constraints on Mixings

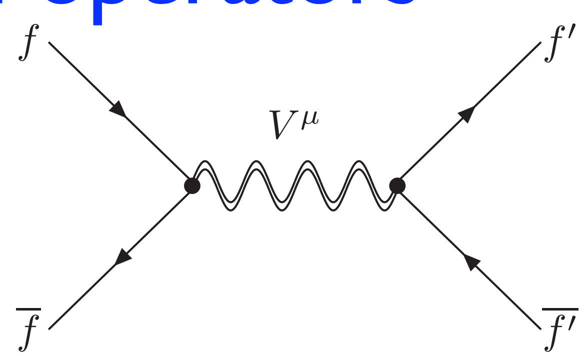
$$U \sim \frac{yv}{M}$$

$M \geq 340\text{GeV} - 3.4\text{TeV}$ for $y = 0.1 - 1$

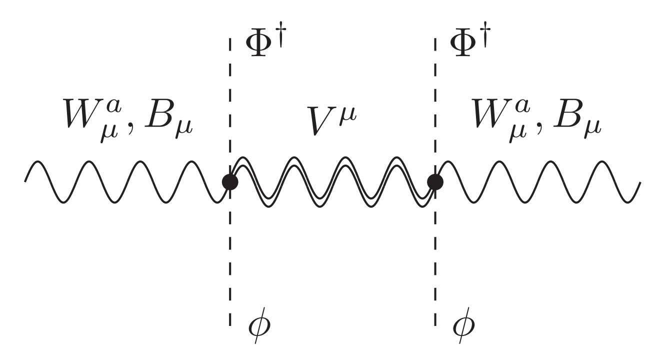
Coupling		N	E	Δ_1	Δ_3	Σ_0	Σ_1
Only with e	$\|U\| <$	0.051	0.020	0.020	0.028	0.020	0.016
	$\|U_{\min}\| =$	0.023	0	0	0.019	0.012	0
Only with μ	$\|U\| <$	0.031	0.029	0.048	0.028	0.018	0.024
	$\|U_{\min}\| =$	0.012	0.014	0.033	0	0	0.005
Only with τ	$\|U\| <$	0.087	0.033	0.035	0.045	0.030	0.029
	$\|U_{\min}\| =$	0.056	0	0	0.027	0.016	0
Universal	$\|U\| <$	0.028	0.019	0.020	0.025	0.017	0.013
	$\|U_{\min}\| =$	0.013	0	0	0.014	0.010	0

General Extra Vectors

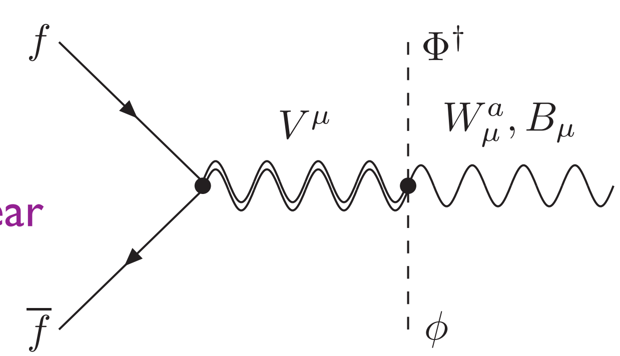
- Spin 1 particles
- GUT, Xdims, Technicolor, Little Higgs, ...
- Candidates for early discovery at LHC
- Contribute to EWPT via mixing with SM gauge bosons and four fermion operators



Four fermion



Oblique



Trilinear

All Types of Extra Vectors

Vector	$\mathcal{B}_\mu$	$\mathcal{B}^1_\mu$	$\mathcal{W}_\mu$	$\mathcal{W}^1_\mu$	$\mathcal{G}_\mu$	$\mathcal{G}^1_\mu$	$\mathcal{H}_\mu$	$\mathcal{L}_\mu$
Irrep	$(1,1)_0$	$(1,1)_1$	$(1,\mathrm{Adj})_0$	$(1,\mathrm{Adj})_1$	$(\mathrm{Adj},1)_0$	$(\mathrm{Adj},1)_1$	$(\mathrm{Adj},\mathrm{Adj})_0$	$(1,2)_{-\frac{3}{2}}$

Vector	$\mathcal{U}^2_\mu$	$\mathcal{U}^5_\mu$	$\mathcal{Q}^1_\mu$	$\mathcal{Q}^5_\mu$	$\mathcal{X}_\mu$	$\mathcal{Y}^1_\mu$	$\mathcal{Y}^5_\mu$
Irrep	$(3,1)_{\frac{2}{3}}$	$(3,1)_{\frac{5}{3}}$	$(3,2)_{\frac{1}{6}}$	$(3,2)_{-\frac{5}{6}}$	$(3,\mathrm{Adj})_{\frac{2}{3}}$	$(\bar{6},2)_{\frac{1}{6}}$	$(\bar{6},2)_{-\frac{5}{6}}$

Quantum numbers determine possible couplings. For instance,

$$\mathcal{L} \supset \mathcal{B}^1_\mu \left[\left(g^{du}_{\mathcal{B}^1} \right)_{ij} \overline{d^i_R} \gamma^\mu u^j_R + g^{\phi}_{\mathcal{B}^1} iD^\mu \phi^T i\sigma_2 \phi \right]$$

$\mathcal{B}^1$ → Pair of Charged vectors

Electroweak breaking: $\mathcal{W}$ → { One neutral vector + Pair of Charged vectors

...

Examples of Symmetry Breaking Patterns

Vector	Model
$\mathcal{B}_\mu$	$U(1)'$, Extra Dimensions
$\mathcal{B}^1_\mu$	$SU(2)_R \otimes U(1)_X \to U(1)_Y$
$\mathcal{W}_\mu$	$SU(2)_1 \otimes SU(2)_2 \to SU(2)_D \equiv SU(2)_L$, Extra Dimensions
$\mathcal{W}^1_\mu$	$SU(4) \to U(1) \otimes (SU(3) \to SU(2))$
$\mathcal{G}_\mu$	$SU(3)_1 \otimes SU(3)_2 \to SU(3)_D \equiv SU(3)_c$, Extra Dimensions
$\mathcal{G}^1_\mu$	$SO(12) \to (SO(8) \to SU(3)) \otimes (SU(2) \otimes SU(2) \to SU(2)_D \to U(1)_Y)$
$\mathcal{H}_\mu$	$SU(6) \to SU(3) \otimes SU(2)$
$\mathcal{L}_\mu$	$G_2 \to SU(2) \otimes (SU(2) \to U(1)_Y)$
$\mathcal{U}^2_\mu$, $\mathcal{U}^5_\mu$	$SU(4) \to SU(3) \otimes U(1)$
$\mathcal{Q}^1_\mu$, $\mathcal{Q}^5_\mu$	$SU(5) \to SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$
$\mathcal{X}_\mu$	$SU(6) \to U(1) \otimes SU(3) \otimes (SU(3) \to SU(2))$
$\mathcal{Y}^1_\mu$, $\mathcal{Y}^5_\mu$	$F_4 \to SU(3) \otimes (SU(3) \to SU(2) \otimes U(1))$

Limits on General Extra Vectors $G \sim \frac{g}{M}$

Vector V_μ	$-\Delta\chi^2_{\rm min}$ ($\chi^2_{\rm min}$/d.o.f.)	Parameter $G^k_V \equiv g^k_V/M_V$	Best Fit [TeV^{-1}]	Bounds [TeV^{-1}]	C.L.
$\mathcal{B}_\mu$	7.35	$G^\phi_\mathcal{B}$	-0.045	$[-0.098,\ \ 0.098]$	95%
	(0.77)	$G^l_\mathcal{B}$	0.021	$[-0.210,\ \ 0.210]$	95%
		$G^q_\mathcal{B}$	-0.89	-	-
		$G^e_\mathcal{B}$	0.048	$[-0.300,\ \ 0.300]$	95%
		$G^u_\mathcal{B}$	-2.6	-	-
		$G^d_\mathcal{B}$	-6.0	-	-
$\mathcal{W}_\mu$	1.51	$G^\phi_\mathcal{W}$	0.002	$[-0.12,\ \ 0.12]$	1 σ
	(0.79)	$G^l_\mathcal{W}$	0.004	$[-0.26,\ \ 0.26]$	95%
		$G^q_\mathcal{W}$	-9.6	-	-
$\mathcal{B}^1_\mu$	0.16	$G^\phi_{\mathcal{B}^1}$	$6 \cdot 10^{-4}$	$[-0.11,\ \ 0.11]$	95%
	(0.79)	$G^{du}_{\mathcal{B}^1}$	6.6	-	-
$\mathcal{W}^1_\mu$	0.65 (0.78)	$\lvert G^\phi_{\mathcal{W}^1}\rvert$	0.18	< 0.50	95%
$\mathcal{L}_\mu$	0 (0.79)	$\lvert G^{el}_\mathcal{L}\rvert$	0	$< \begin{pmatrix} 0.29 & 0.33 & 0.39 \\ 0.34 & - & - \\ 0.39 & - & - \end{pmatrix}$	95%

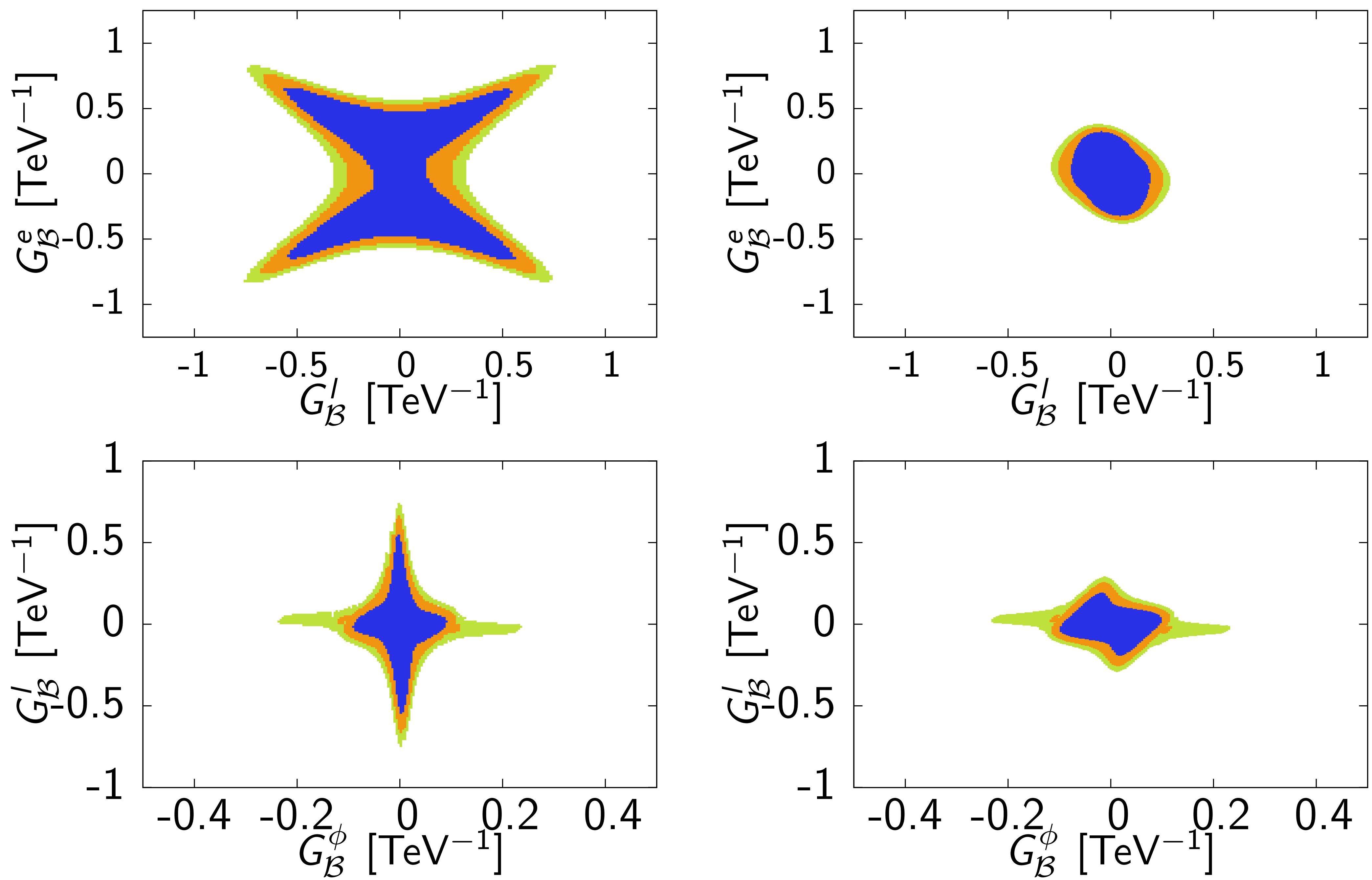
Limits on General Extra Vectors $G \sim \frac{g}{M}$

$\mathcal{U}_\mu^2$	0 (0.79)	$\lvert G^{ed}_{\mathcal{U}^2}\rvert$	0	$<$	$\begin{pmatrix} 0.21 & 0.49 & 0.49 \\ - & - & - \\ - & - & - \end{pmatrix}$	95%
		$\lvert G^{lq}_{\mathcal{U}^2}\rvert$	0	$<$	$\begin{pmatrix} 0.12 & 0.29 & 0.29 \\ 0.56 & 0.65 & - \\ - & - & - \end{pmatrix}$	95%
$\mathcal{U}_\mu^5$	≤ 2.77 (0.77)	$\lvert G^{eu}_{\mathcal{U}^5}\rvert$	0.43 $[1,2]$	$<$	$\begin{pmatrix} 0.25 & 0.62 & - \\ - & - & - \\ - & - & - \end{pmatrix}$	95%
$\mathcal{Q}_\mu^1$	≤ 0.45 (0.79)	$\lvert G^{ul}_{\mathcal{Q}^1}\rvert$	0.27 $[1,2]$	$<$	$\begin{pmatrix} 0.22 & 0.54 & - \\ 0.57 & - & - \\ - & - & - \end{pmatrix}$	95%
$\mathcal{Q}_\mu^5$	≤ 3.36 (0.78)	$\lvert G^{dl}_{\mathcal{Q}^5}\rvert$	0.87 $[1,1]$	$<$	$\begin{pmatrix} 1.06 & 0.58 & - \\ 1.07 & - & - \\ 1.07 & - & - \end{pmatrix}$	95%
		$\lvert G^{eq}_{\mathcal{Q}^5}\rvert$	0.64 $[1,1]$	$<$	$\begin{pmatrix} 0.78 & 1.0 & 1.2 \\ - & - & - \\ - & - & - \end{pmatrix}$	95%
$\mathcal{X}_\mu$	≤ 2.86 (0.77)	$\lvert G^{lq}_{\mathcal{X}}\rvert$	0.65 $[1,2]$	$<$	$\begin{pmatrix} 0.27 & 0.93 & 0.57 \\ 1.04 & 1.40 & - \\ - & - & - \end{pmatrix}$	95%

Z' Bosons: New Singlets $\mathcal{B}$

Lepton and Higgs couplings

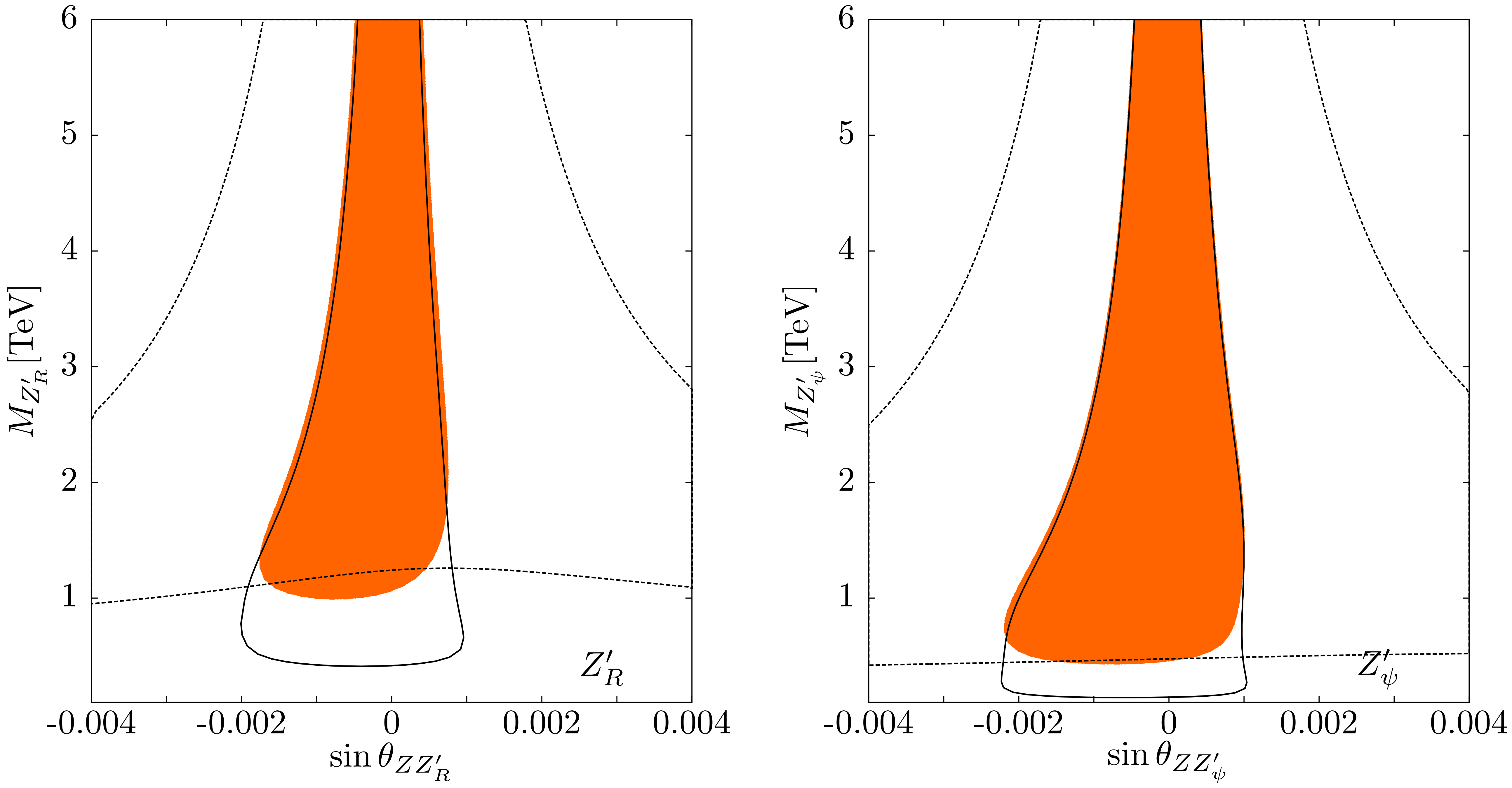
Without LEP 2 | All Observables



Popular Z' Models

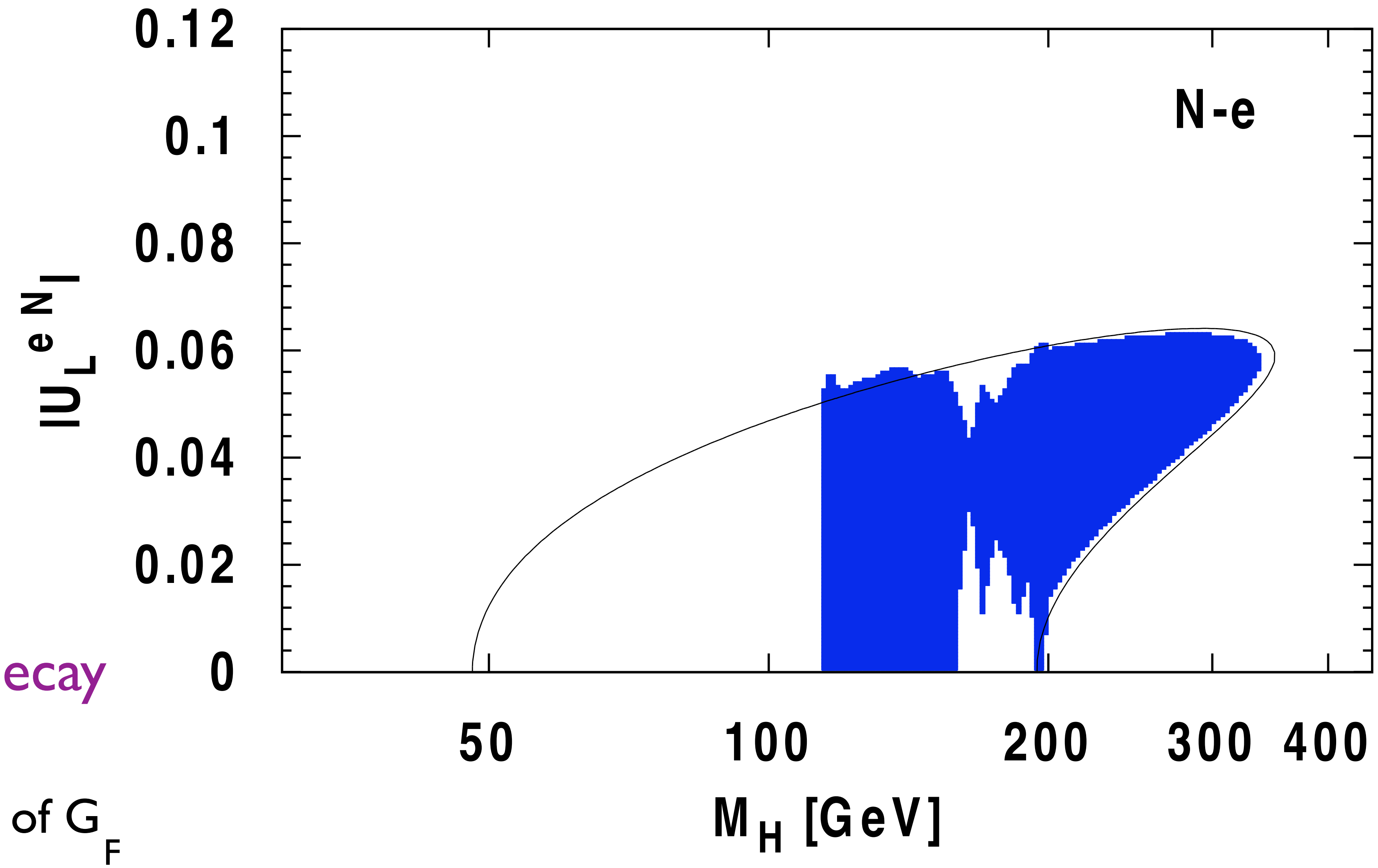
Model	95% C.L. Electroweak Limits on $\sin\theta_{ZZ'}$ $[\times 10^{-4}]$ EWPD (no LEP 2)	LEP 2	All Data	$M_{Z'}$ [TeV] EWPD (no LEP 2)	LEP 2	All Data
Z'_χ	$[-10, 7]$	$[-80, 118]$	$[-11, 7]$	1.123	0.772	1.022
Z'_ψ	$[-19, 7]$	$[-196, 262]$	$[-19, 7]$	0.151	0.455	0.476
Z'_η	$[-22, 25]$	$[-150, 164]$	$[-23, 27]$	0.422	0.460	0.488
Z'_I	$[-5, 9]$	$[-144, 96]$	$[-5, 10]$	1.207	0.652	1.105
Z'_N	$[-14, 6]$	$[-165, 223]$	$[-14, 6]$	0.635	0.421	0.699
Z'_S	$[-9, 5]$	$[-85, 129]$	$[-10, 5]$	1.249	0.728	1.130
Z'_R	$[-17, 7]$	$[-166, 177]$	$[-15, 5]$	0.439	0.724	1.130
Z'_{LR}	$[-13, 5]$	$[-147, 189]$	$[-12, 4]$	0.999	0.667	1.162

Popular Z' Models



New Particles and the Higgs Mass

Extra neutrino singlet, coupled to electron



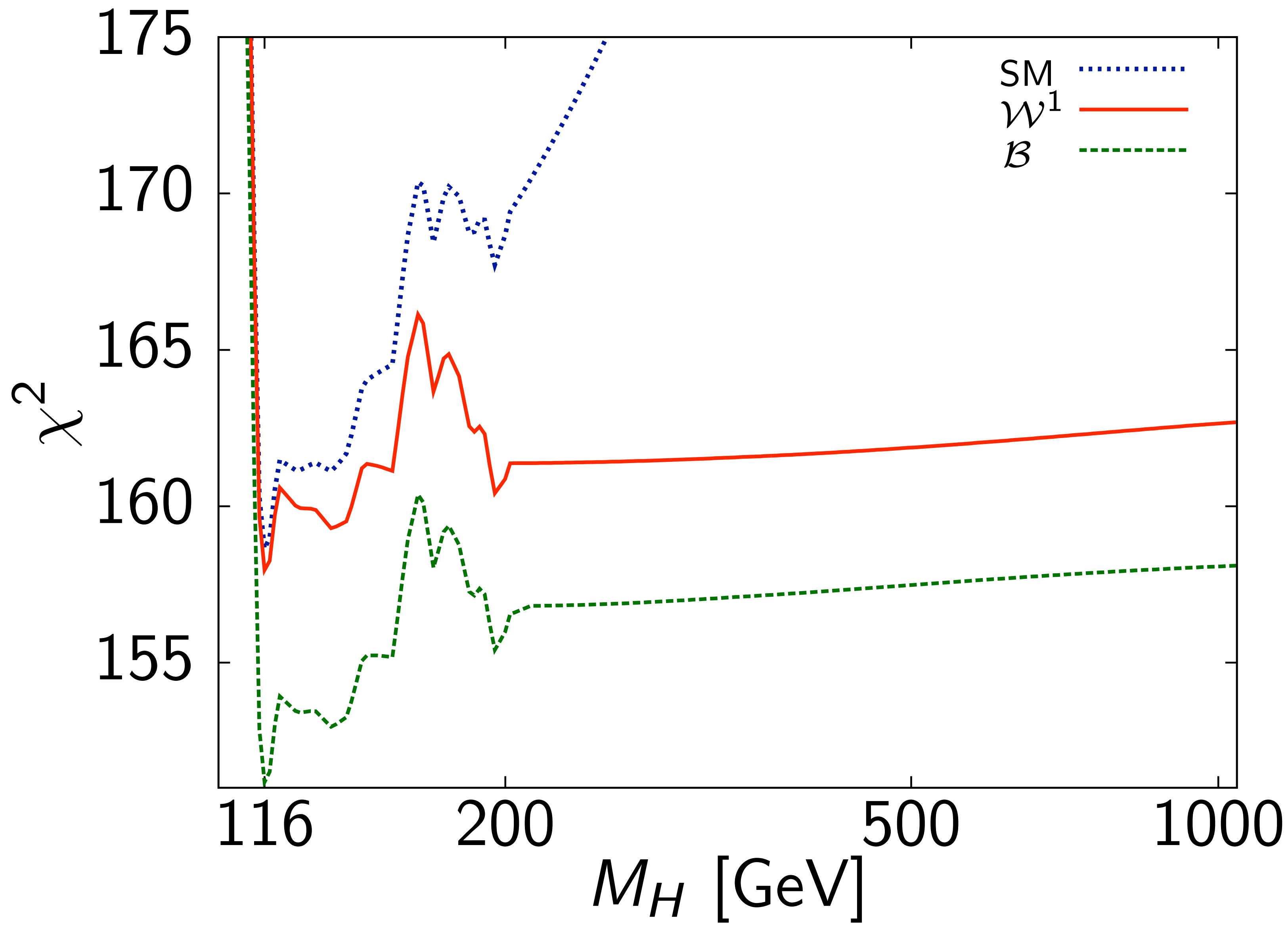
Contributes to muon decay

Extraction of G_F

Changes Δr

New Particles and the Higgs Mass

Vector singlet
and
fermiophobic
vector triplet



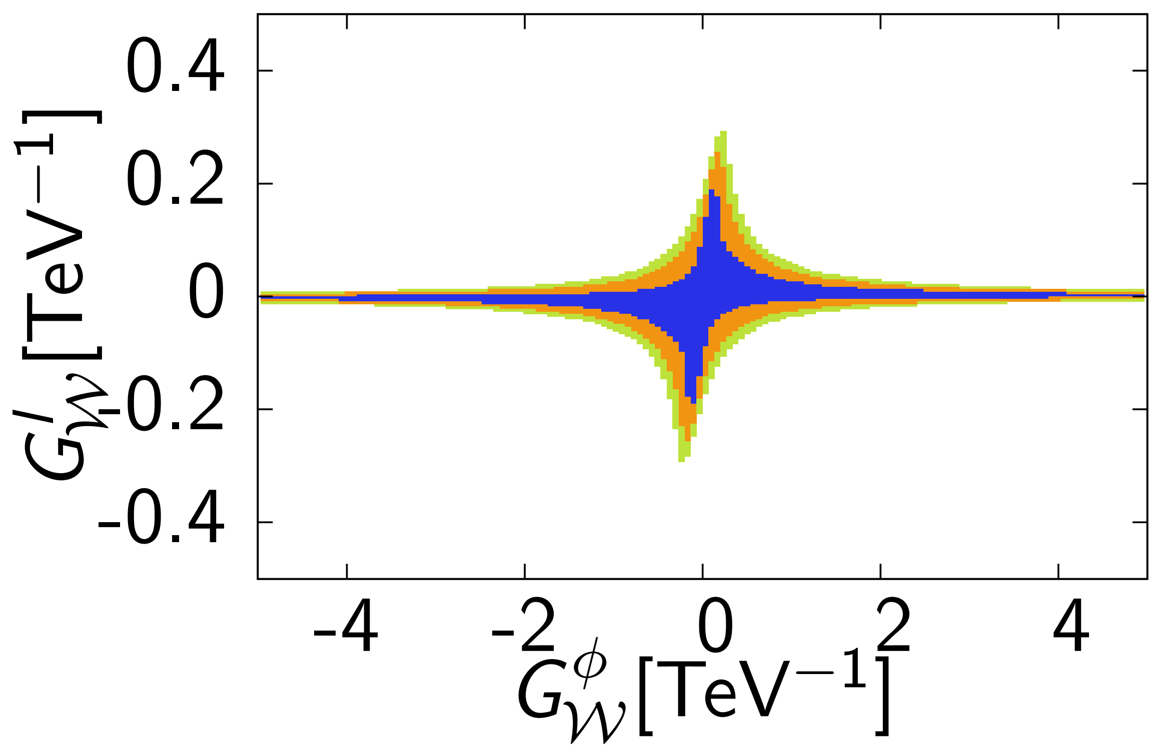
Mixing with Z (and W)

⬇ Shift of masses

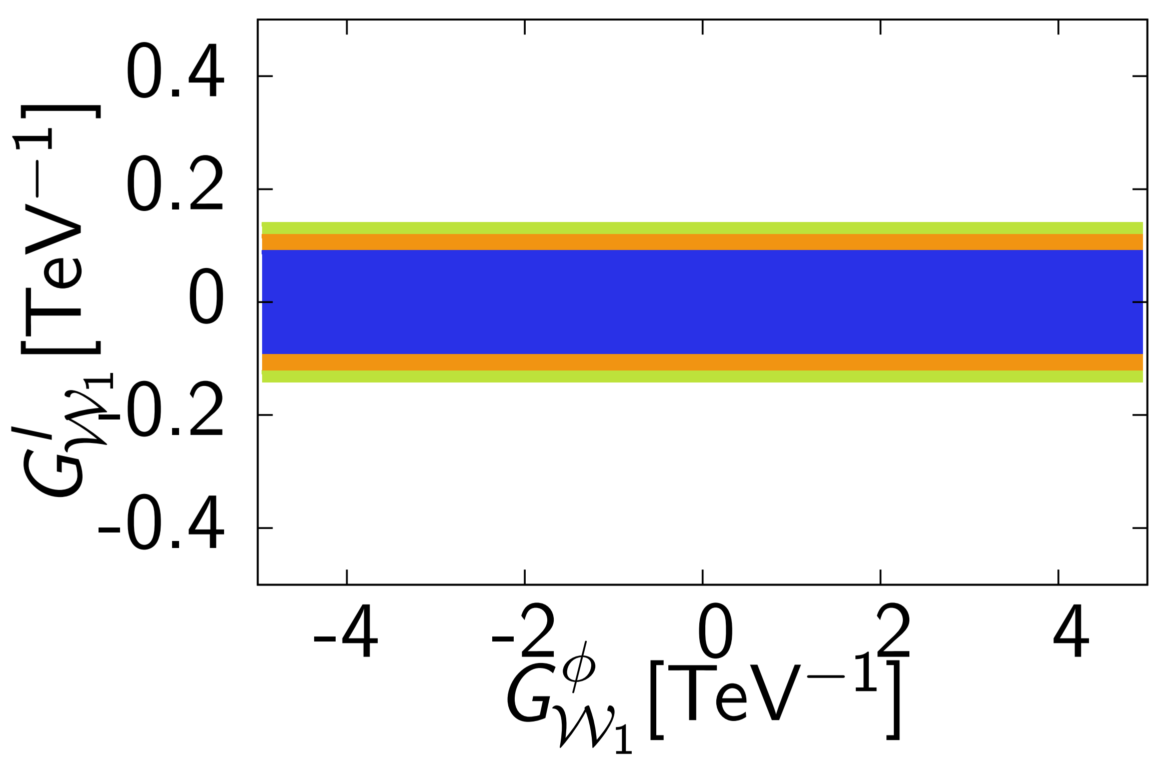
Positive T parameter

Interplay of several new particles

Vector triplet: lepton and Higgs couplings



One $\mathcal{W}$



Two mirror $\mathcal{W}$s

Solving the A^b_{FB} anomaly with Extra Vectors

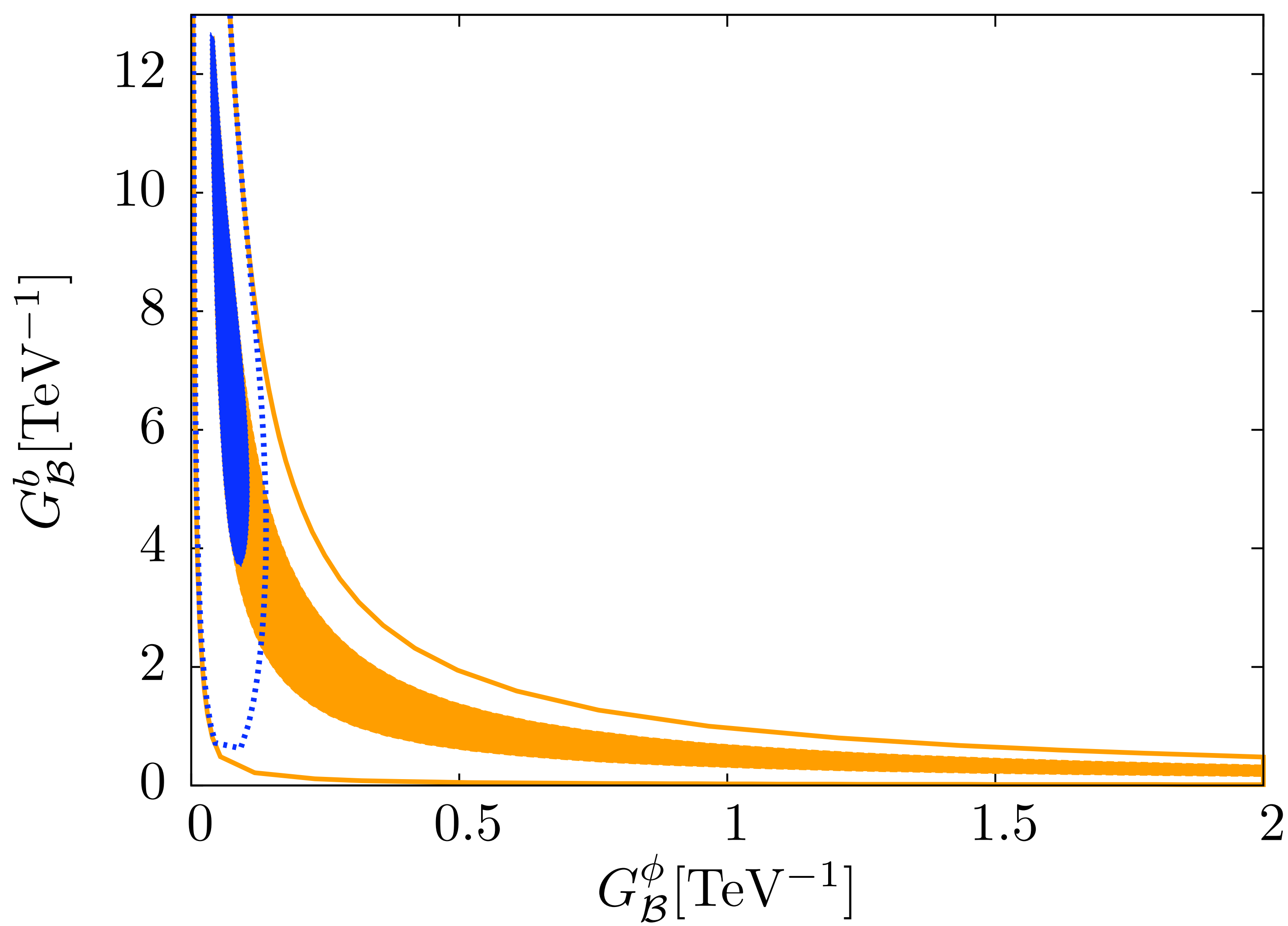
SM with $M_H = 115$ GeV $\rightarrow$ Pull$[A^b_{\rm FB}] = -2.6$

SM with extra neutral (and charged) singlet vector bosons coupling to 3rd family:

	$\mathcal{B}$				$\mathcal{B}+\mathcal{B}^1$	
	Free	$G^b_{\mathcal{B}} \equiv 1$	$M_H = 200\,\mathrm{GeV}$	$M_H = 500\,\mathrm{GeV}$	Free	$G^b_{\mathcal{B}} \equiv 1$
$-\Delta\chi^2_{\rm min}$	8.2	2.7	14.1	47.7	8.2	8.2
Pull$[A^b_{FB}]$	-0.5	-2.5	-0.4	-0.4	-0.5	-0.5
$G^b_{\mathcal{B}}$ [TeV^{-1}]	6.4	1	3.8	2.4	3.2	1
$G^\phi_{\mathcal{B}}$ [TeV^{-1}]	0.082	0.078	0.13	0.19	0.16	0.53
$G^\phi_{\mathcal{B}^1}$ [TeV^{-1}]	-	-	-	-	0.20	0.73

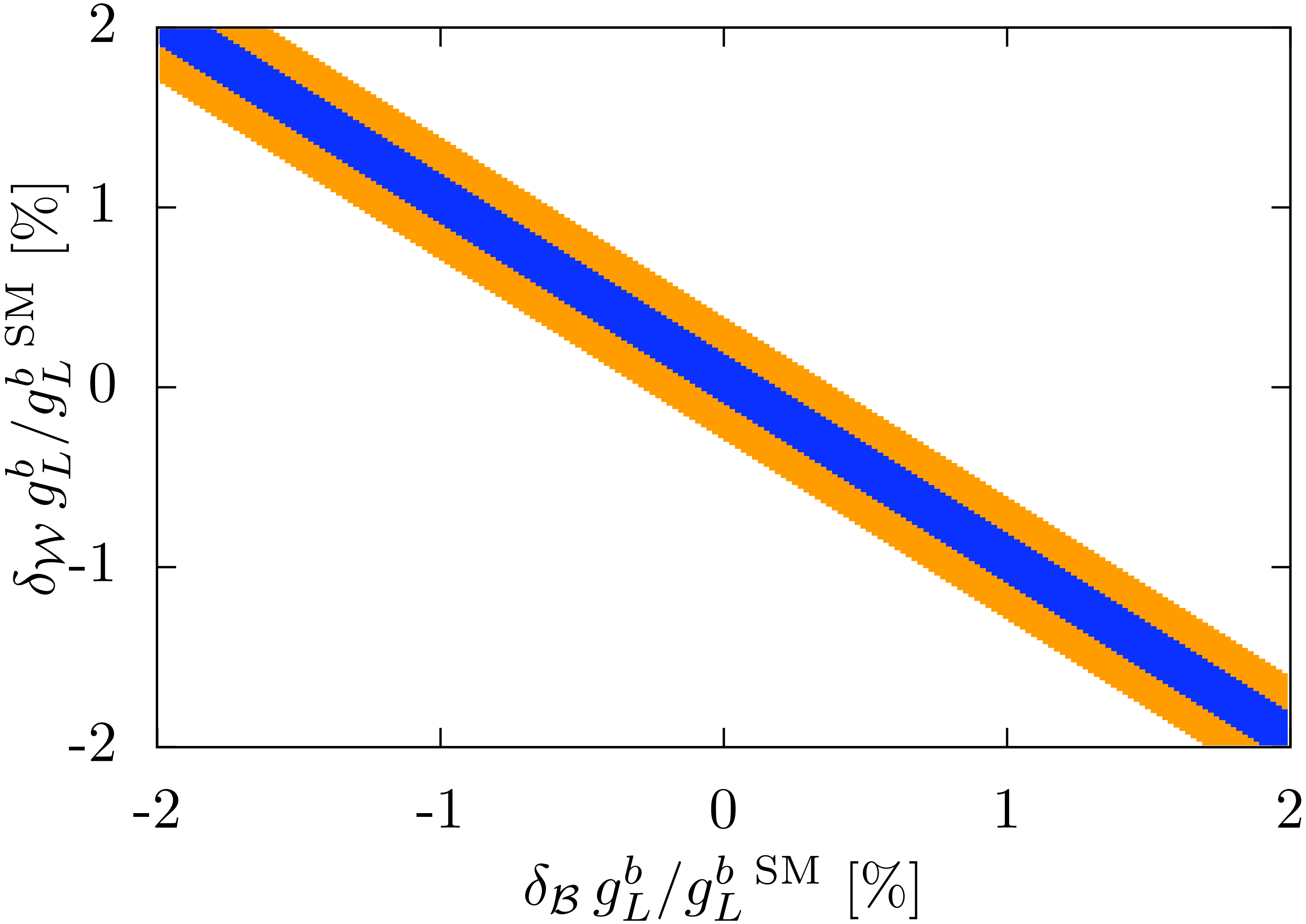
Solving the A_{FB}^{b} anomaly with Extra Vectors

Including $\mathcal{B}^1$ helps in retaining perturbative couplings



"Custodial" protection of $Z \to b\bar{b}$

Cancel singlet against triplet contributions:



No cancellation for $Z \to t\bar{t}$ simultaneously

Conclusions

New particles can be classified into irreps of SM *full* gauge symmetry

With mild assumptions, explicit general Lagrangians can be written

Direct contact with models and with collider physics

Conclusions

Constraints from Precision Electroweak Data

- EWPT place limits on *couplings/masses*
  Different dependence at hadron colliders !
- Mixings of extra leptons and SM leptons constrained enough to make difficult to observe heavy neutrino singlets at LHC
- Leptonic couplings of new vectors small (LEP 2), or large masses
- Hadronic couplings can be large
- Cancellations of the effects of different new particles can open new regions in parameter space
- Correlations with the Higgs mass value

Conclusions

LHC searches

Drell-Yan dilepton resonance $V \to ll$ (neutral vectors)

- Only for $\mathcal{B}$ and $\mathcal{W}$
- Requires large enough couplings
- EWPT + Tevatron → Little space for discovery at 7 TeV and 1 fb^{-1} (better at 14 TeV and 30 fb^{-1})

$V \to l\nu$ (charged vectors)

- Only for $\mathcal{W}$ (or $\mathcal{B}^1$ if light RH neutrinos)
- Similar considerations but larger backgrounds

$V \to jj$, $V \to tt$, $V \to tb$, ...

- Main signals for leptophobic vector bosons
- Less stringent mass limits