Z′ and Friends

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with

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Outline

- Introduction
- General Extra Vector Bosons
- Constraints
- Interplay (Higgs, several new vectors)
- 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 → Restrict parameter space

Discovery ☺ → Check consistency

General Extensions of the SM

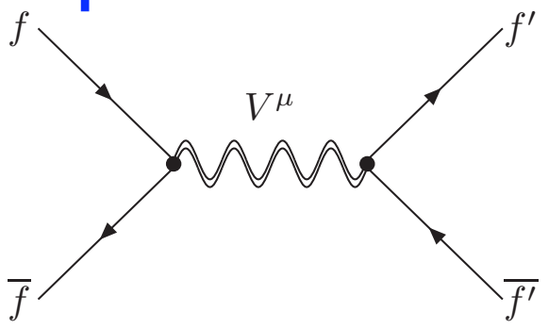
Impose Symmetries! → • Classify particles
• Restrict interactions

Lorentz Invariance →
- Scalars
- Spinors
- Vectors

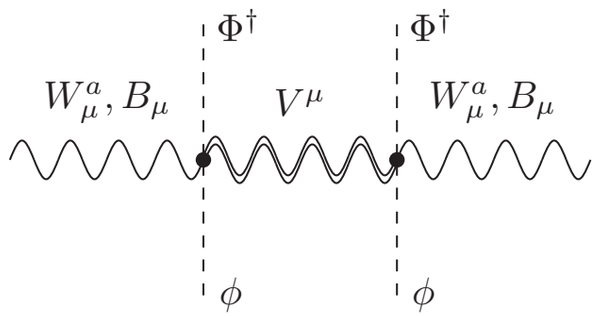
SU(3)xSU(2)xU(1) Gauge Invariance →
- EW singlets, doublets, triplets
- Hypercharged
- Coloured

General Extra Vector Bosons

- 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

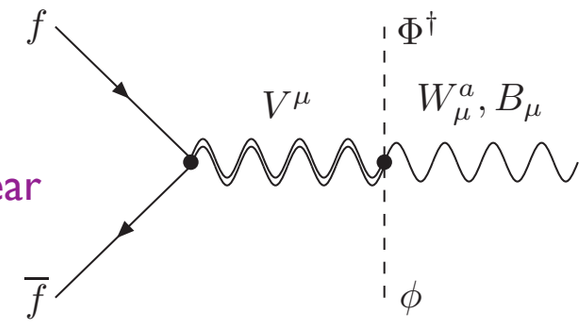


Four fermion



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	$(3,1)_{\frac{2}{3}}$	$(3,1)_{\frac{5}{3}}$	$(3,2)_{\frac{1}{6}}$	$(3,2)_{-\frac{5}{6}}$	$(3,\mathrm{Adj})_{\frac{2}{3}}$	$(\bar{6},2)_{\frac{1}{6}}$	$(\bar{6},2)_{-\frac{5}{6}}$

Electroweak breaking:

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

$\mathcal{W}$ ⇒ { One neutral vector + Pair of Charged vectors

...

All Types of Extra Vectors

Z′ W′

Vector	$\mathcal{B}_\mu$	$\mathcal{B}^1_\mu$	$\mathcal{W}_\mu$	$\mathcal{W}^1_\mu$	$\mathcal{G}_\mu$	$\mathcal{G}^1_\mu$	$\mathcal{H}_\mu$	$\mathcal{L}_\mu$
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All Types of Extra Vectors

Leptophilic

Color octets

Fermiophobic

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	$(1,1)_0$	$(1,1)_1$	$(1,\mathrm{Adj})_0$	$(1,\mathrm{Adj})_1$	$(\mathrm{Adj},1)_0$	$(\mathrm{Adj},1)_1$	$(\mathrm{Adj},\mathrm{Adj})_0$	$(1,2)_{-\frac{3}{2}}$

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Leptoquarks

Quarkphilic

All Types of Extra Vectors

Vector	$\mathcal{B}_\mu$	$\mathcal{B}^1_\mu$	$\mathcal{W}_\mu$	$\mathcal{W}^1_\mu$	$\mathcal{G}_\mu$	$\mathcal{G}^1_\mu$	$\mathcal{H}_\mu$	$\mathcal{L}_\mu$
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Quantum numbers determine possible couplings. For instance,

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

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
$\mathcal{G}^1_\mu$	$SO(12) \to (SO(8) \to SU(3)) \otimes (SU(2) \otimes SU(2) \to SU(2)_D \to U(1)_Y)$
$\mathcal{H}_\mu$	$SU(6) \to SU(3) \otimes SU(2)$
$\mathcal{L}_\mu$	$G_2 \to SU(2) \otimes (SU(2) \to U(1)_Y)$
$\mathcal{U}^2_\mu,\ \mathcal{U}^5_\mu$	$SU(4) \to SU(3) \otimes U(1)$
$\mathcal{Q}^1_\mu,\ \mathcal{Q}^5_\mu$	$SU(5) \to SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$
$\mathcal{X}_\mu$	$SU(6) \to U(1) \otimes SU(3) \otimes (SU(3) \to SU(2))$
$\mathcal{Y}^1_\mu,\ \mathcal{Y}^5_\mu$	$F_4 \to SU(3) \otimes (SU(3) \to SU(2) \otimes U(1))$

Impact on EW precision tests

Vector	Z pole $e^+e^- \to \bar{f}f$	M_W	CKM	ν-N DIS	NC $\nu e \to \nu e$	APV	PV in $e^-e^- \to e^-e^-$	LEP 2 $e^+e^- \to \bar{f}f$
$\mathcal{B}_\mu$	✓	✓	✓	✓	✓	✓	✓	✓
$\mathcal{W}_\mu$	✓	✓	✓	✓	✓	✓	✓	✓
$\mathcal{G}_\mu$								
$\mathcal{H}_\mu$								
$\mathcal{B}^1_\mu$	✓	✓	✓	✓	✓	✓	✓	✓
$\mathcal{W}^1_\mu$	✓	✓		✓	✓	✓	✓	✓
$\mathcal{G}^1_\mu$								
$\mathcal{L}_\mu$					✓			✓
$\mathcal{U}^2_\mu$			✓	✓		✓		✓
$\mathcal{U}^5_\mu$						✓		✓
$\mathcal{Q}^1_\mu$				✓		✓		✓
$\mathcal{Q}^5_\mu$				✓		✓		✓
$\mathcal{X}_\mu$			✓	✓		✓		✓
$\mathcal{Y}^1_\mu$								
$\mathcal{Y}^5_\mu$								

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

Vector V_μ	$-\Delta\chi^2_{\rm min}$ $(\chi^2_{\rm min}/{\rm d.o.f.})$	Parameter $G_V^k \equiv g_V^k/M_V$	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	$[-0.12,\ \ 0.12]$	$1\ \sigma$
	(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	$G^\phi_{\mathcal{B}^1}$	$6\cdot10^{-4}$	$[-0.11,\ \ 0.11]$	95%
	(0.79)	$G^{du}_{\mathcal{B}^1}$	6.6	-	-
$\mathcal{W}^1_\mu$	0.65	$\lvert G^\phi_{\mathcal{W}^1}\rvert$	0.18	< 0.50	95%
	(0.78)				
$\mathcal{L}_\mu$	0	$\lvert G^{el}_{\mathcal{L}}\rvert$	0	$< \begin{pmatrix} 0.29 & 0.33 & 0.39 \\ 0.34 & - & - \\ 0.39 & - & - \end{pmatrix}$	95%
	(0.79)				

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

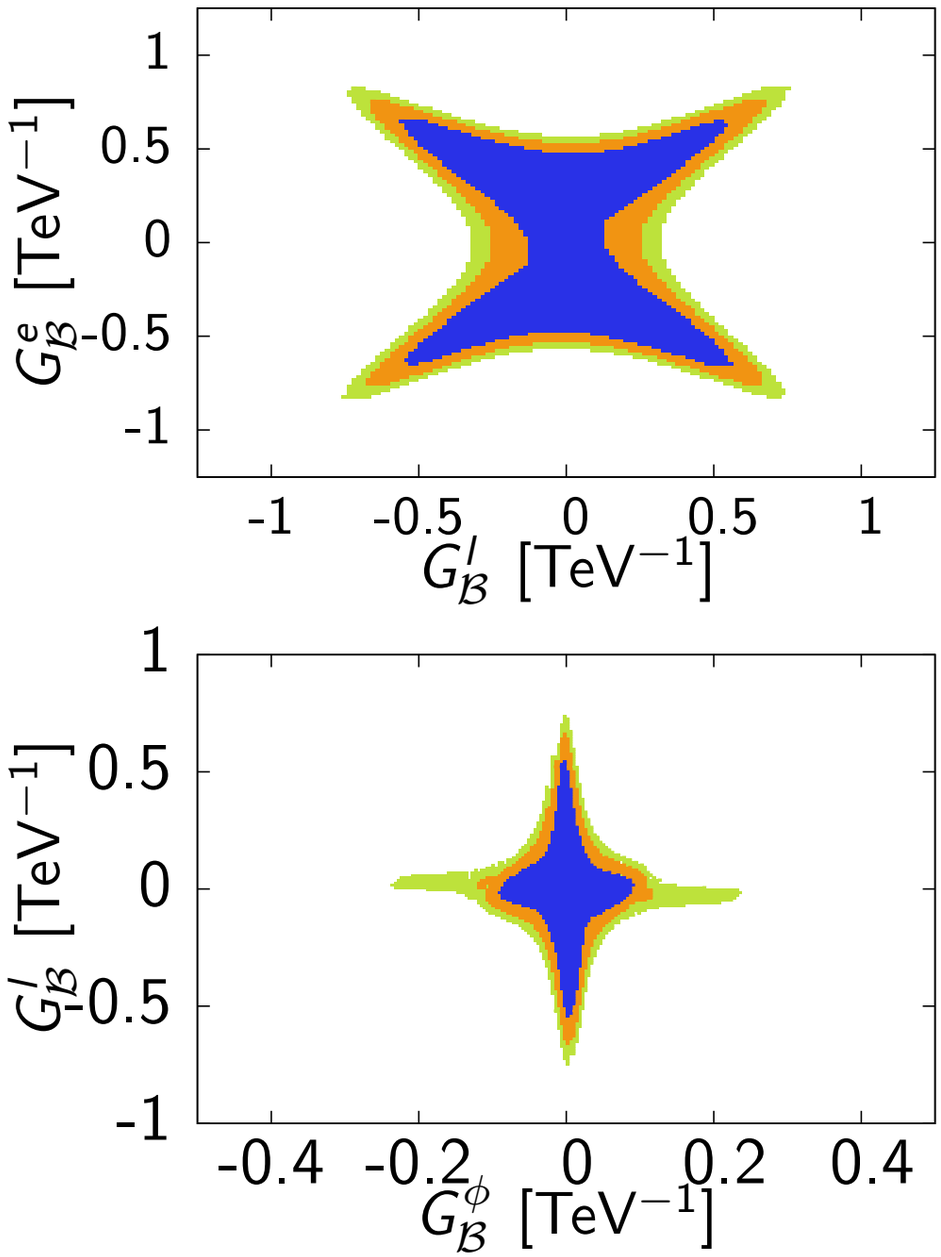
$\mathcal{U}_\mu^2$	0 (0.79)	$\lvert G^{ed}_{\mathcal{U}^2}\rvert$	0	$< \begin{pmatrix} 0.21 & 0.49 & 0.49 \\ - & - & - \\ - & - & - \end{pmatrix}$	95%
		$\lvert G^{lq}_{\mathcal{U}^2}\rvert$	0	$< \begin{pmatrix} 0.12 & 0.29 & 0.29 \\ 0.56 & 0.65 & - \\ - & - & - \end{pmatrix}$	95%
$\mathcal{U}_\mu^5$	≤ 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%

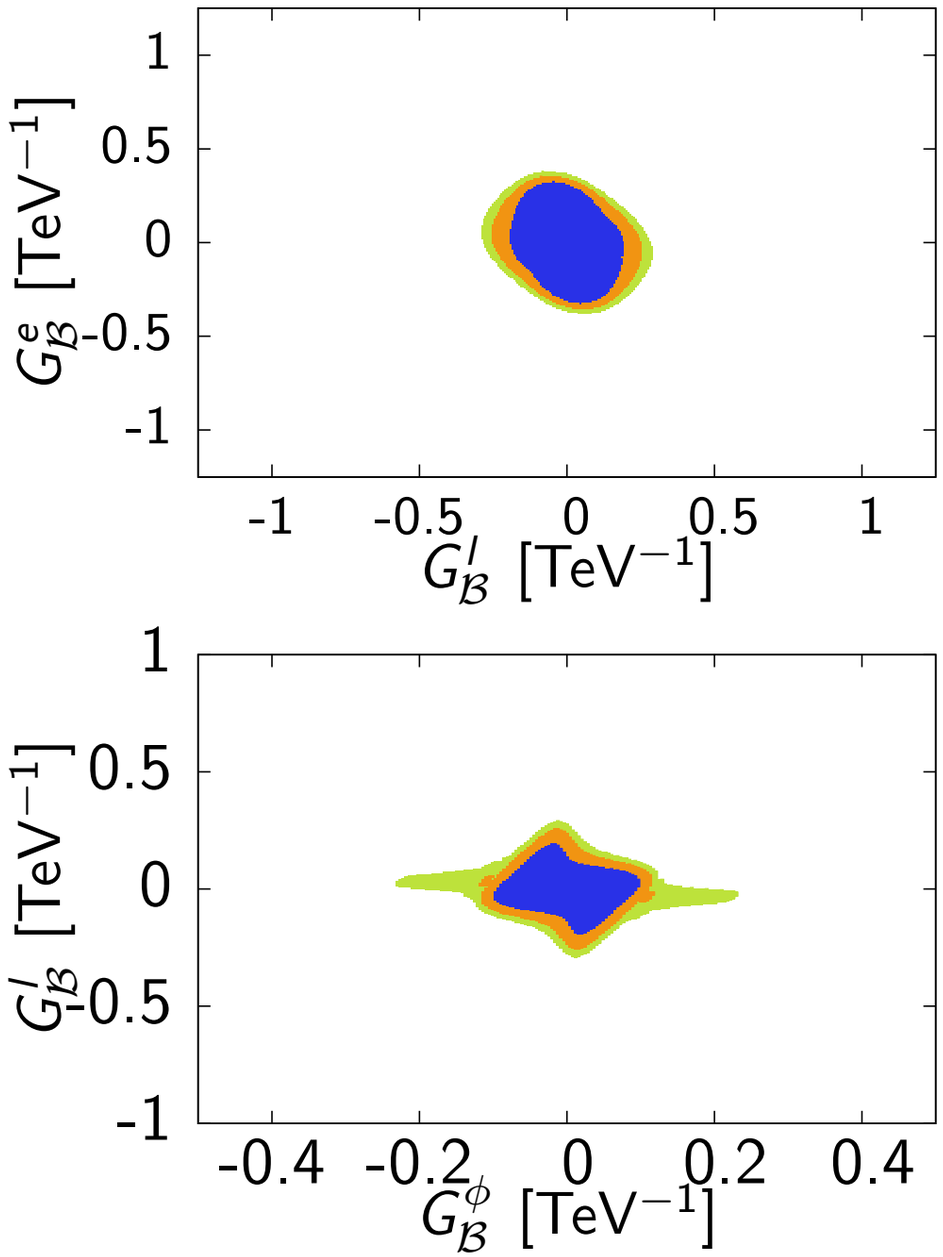
Z' Bosons: New Singlets $\mathcal{B}$

Without LEP 2

All Observables

Lepton and Higgs couplings

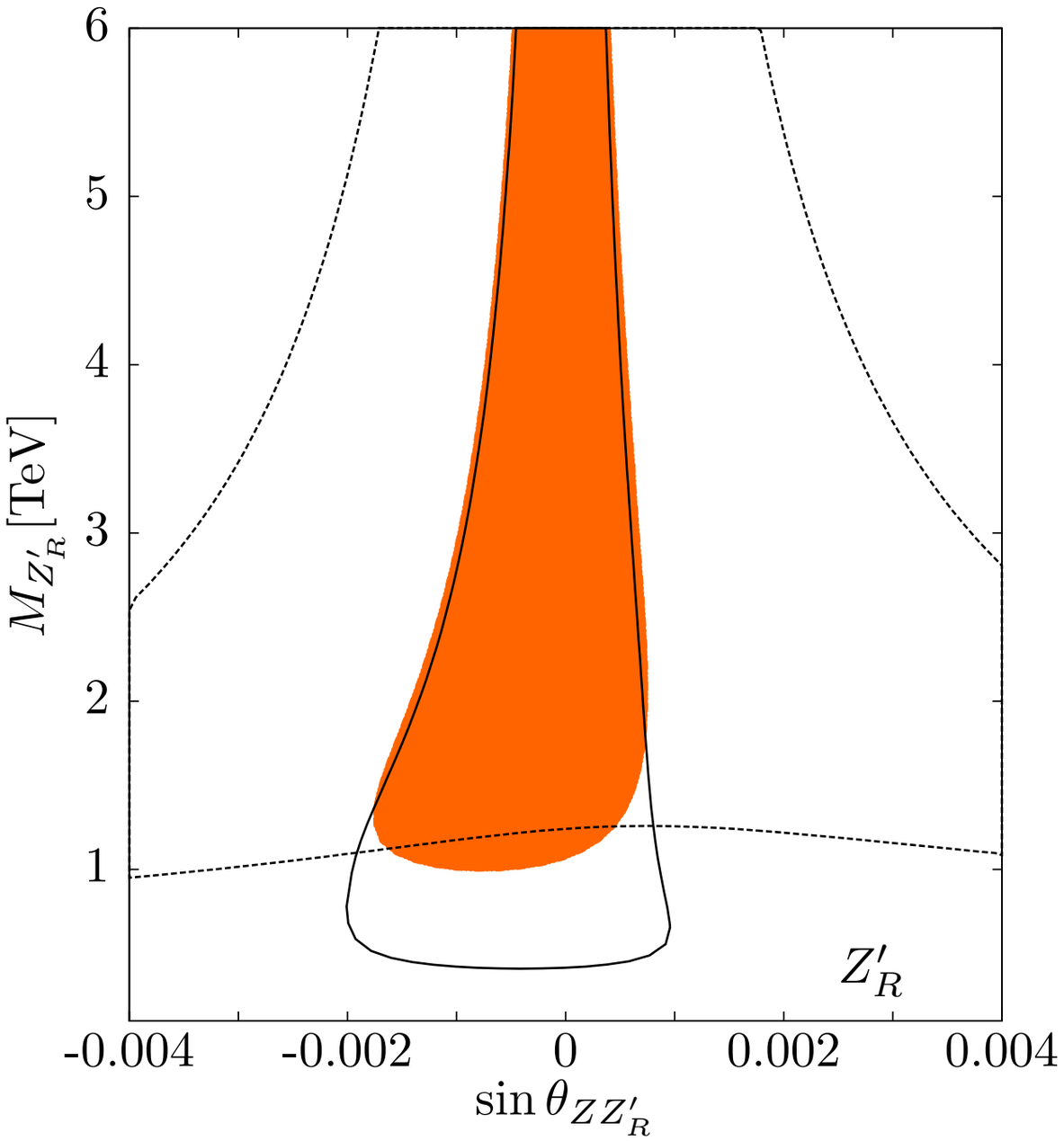


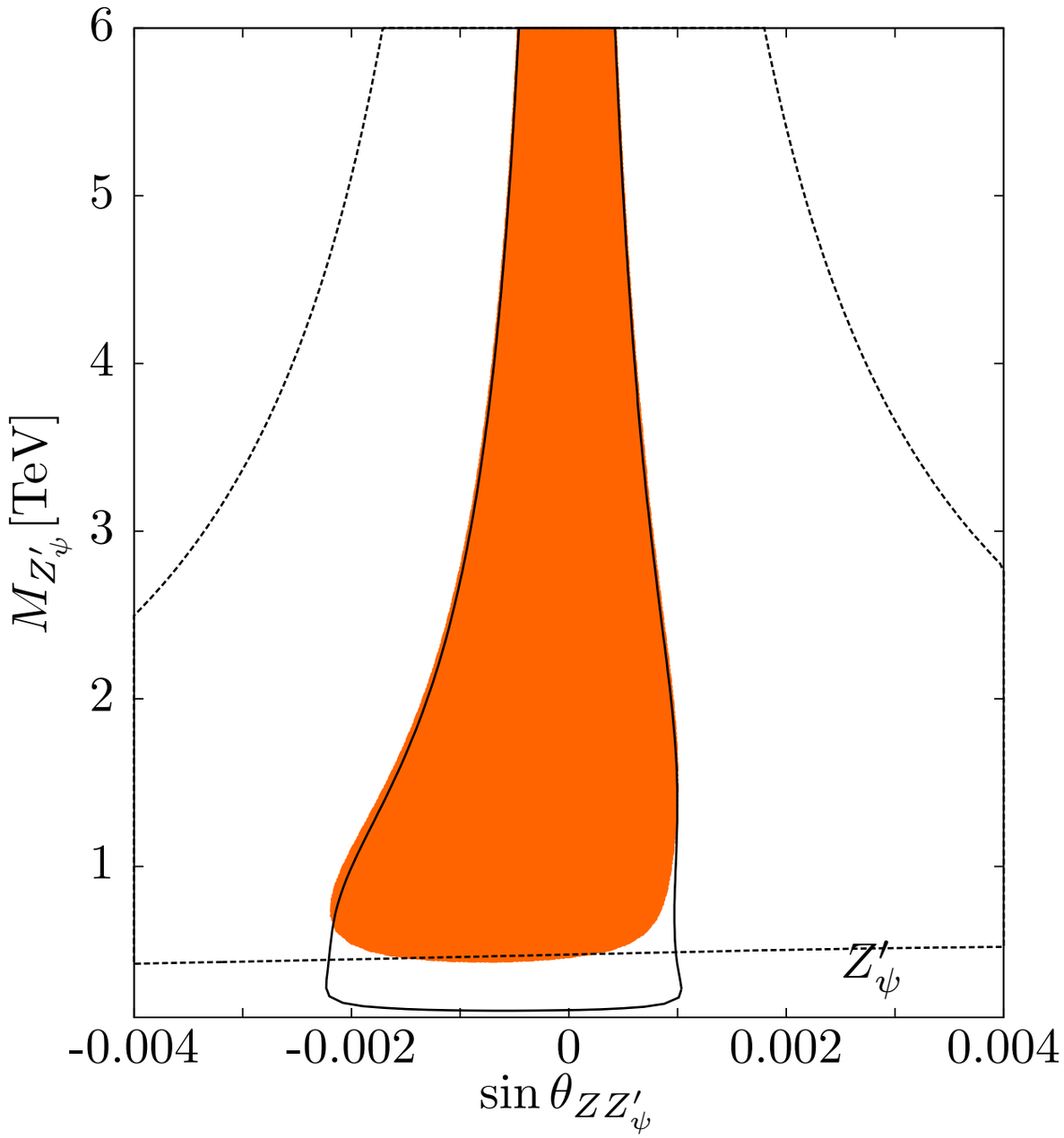


Popular Z' Models

Model	95% C.L. Electroweak Limits on $\sin\theta_{ZZ'}\ [\times 10^{-4}]$			95% C.L. Electroweak Limits on $M_{Z'}$ [TeV]		
	EWPD (no LEP 2)	LEP 2	All Data	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

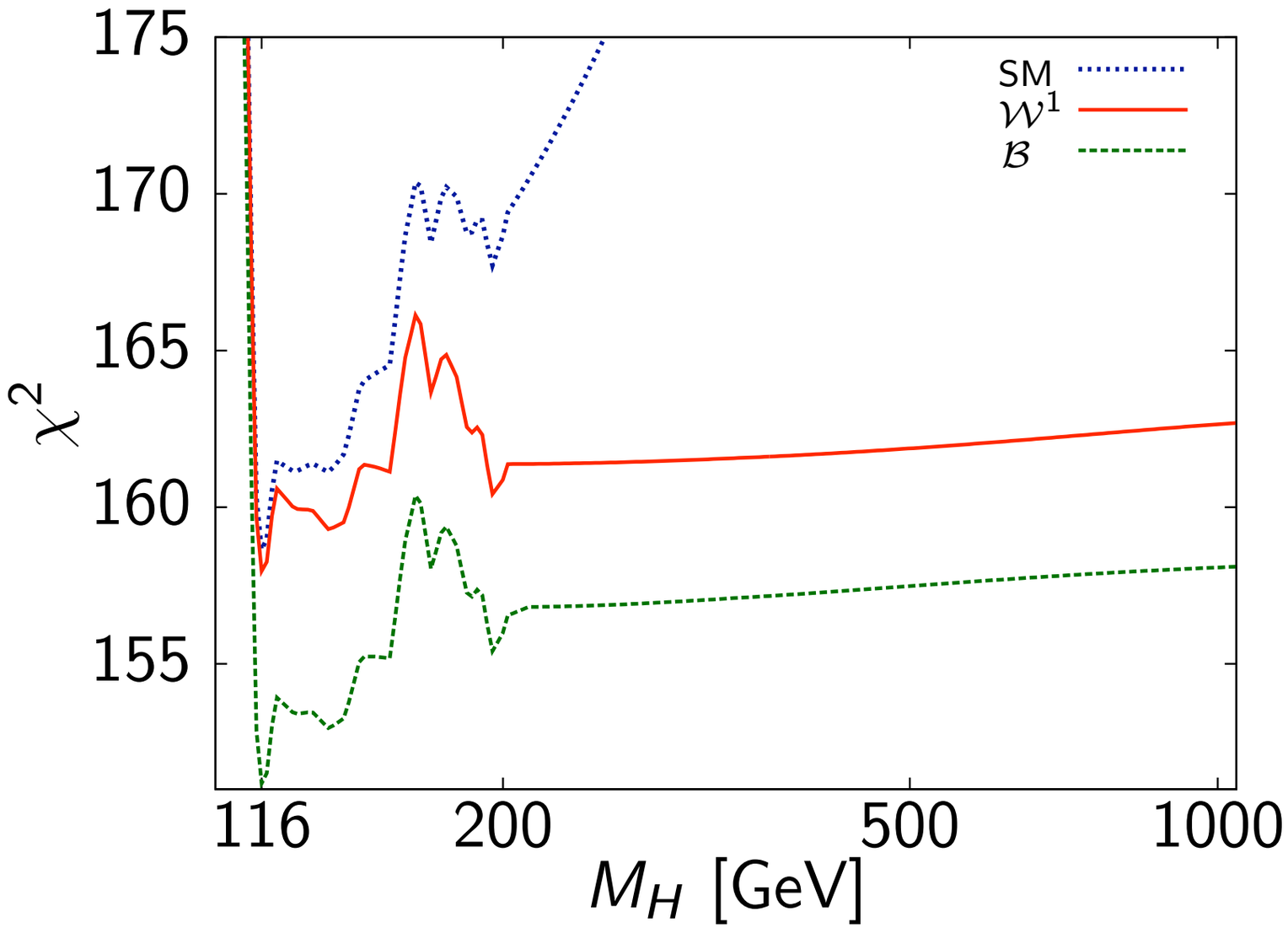
Popular Z' Models





New Vectors and the Higgs Mass

Vector singlet and fermiophobic vector triplet



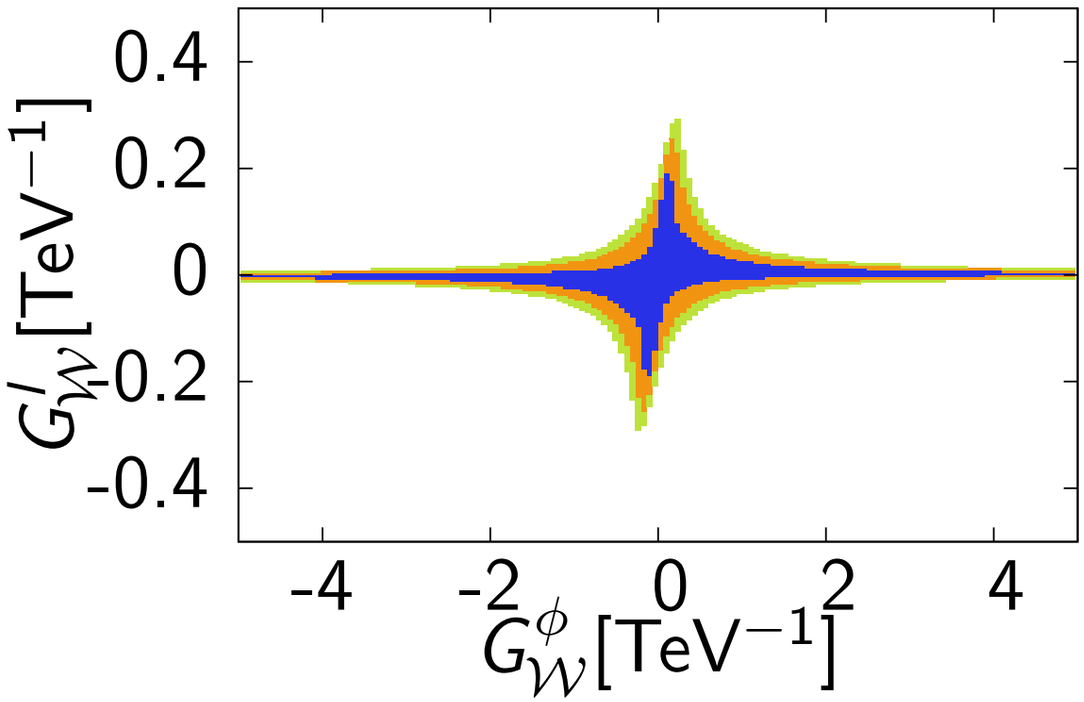
Mixing with Z (and W)

⇩ Shift of masses

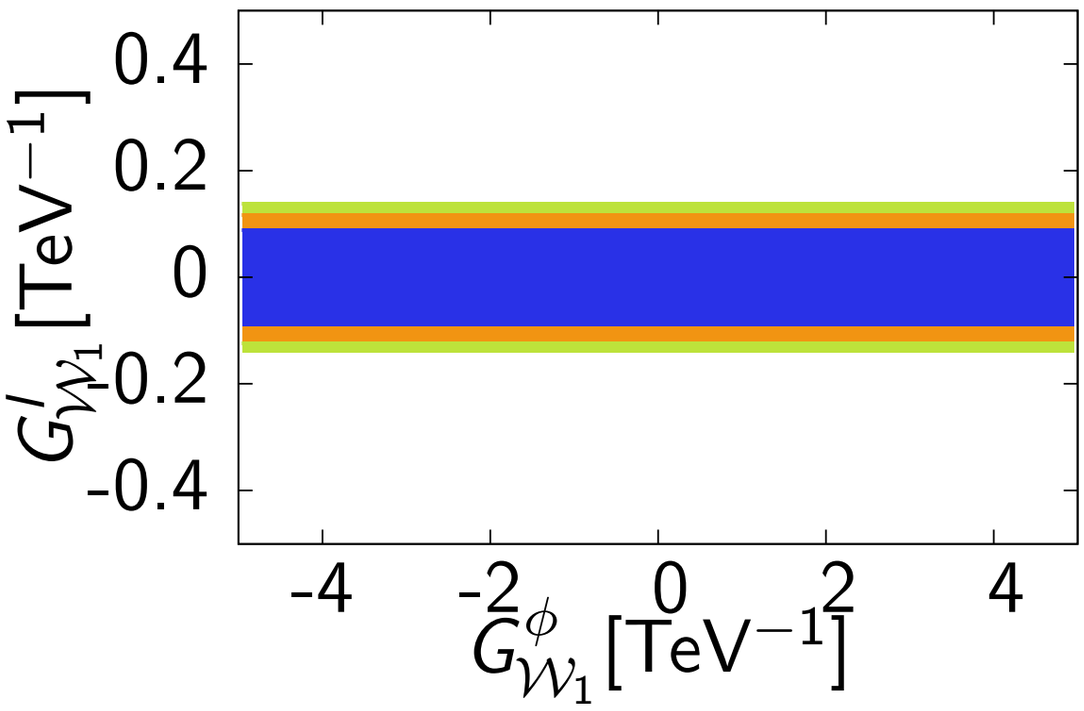
Positive T parameter

Interplay of several new vectors

Vector triplet: lepton and Higgs couplings



One $\mathcal{W}$



Two mirror $\mathcal{W}$s

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

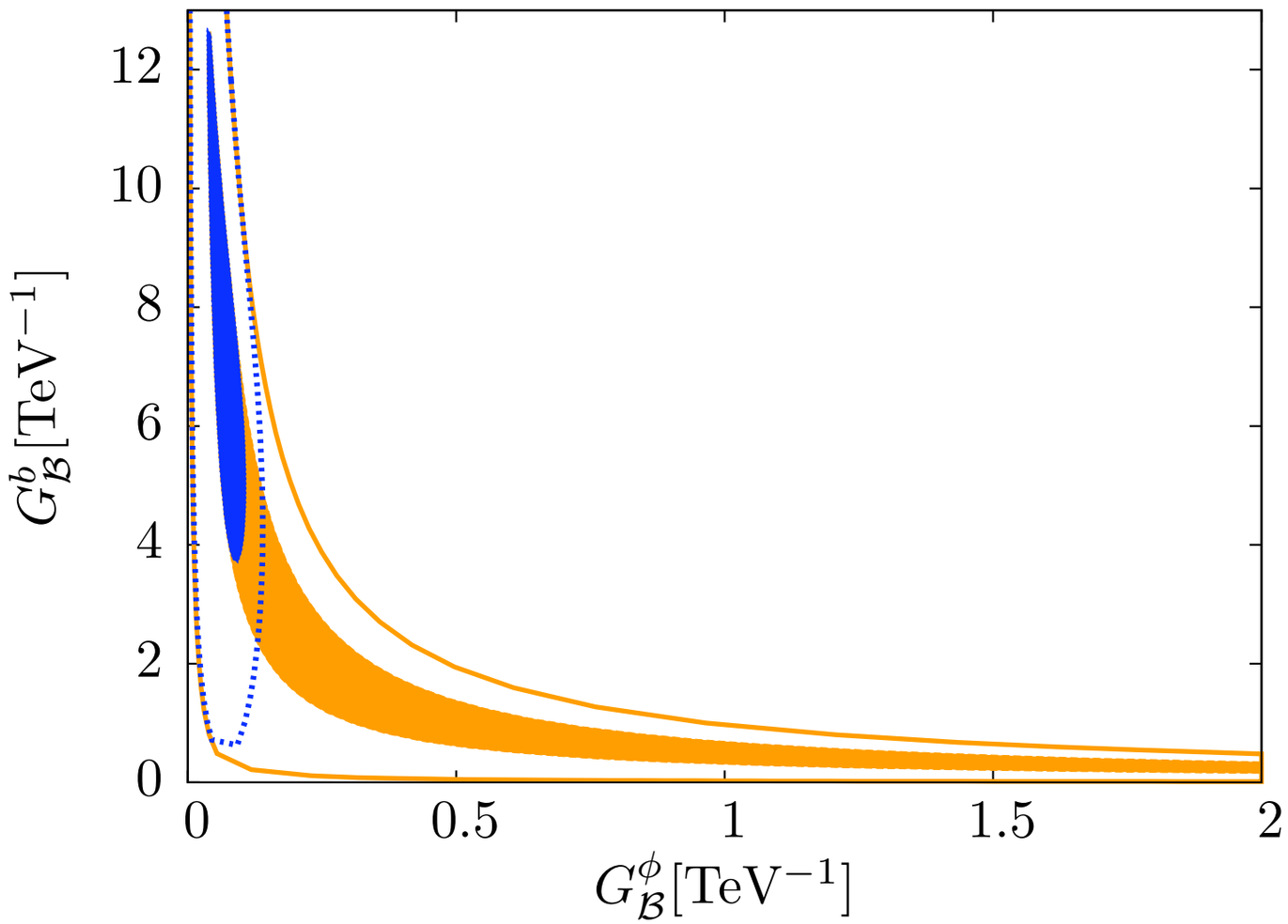
SM with $M_H = 115$ GeV $\longrightarrow$ Pull$[A_{\rm FB}^b] = -2.6$

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

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

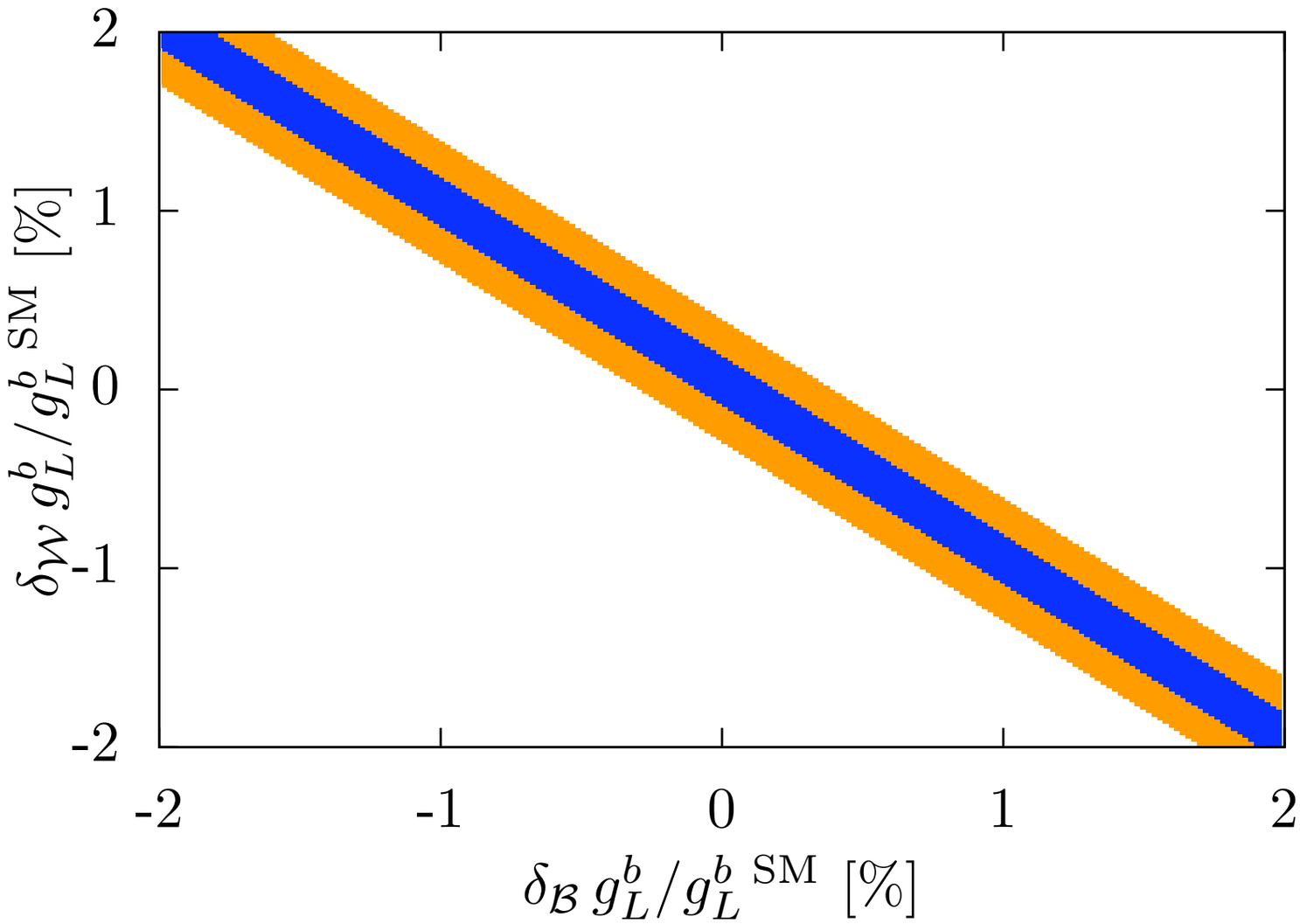
Solving the A_{FB}^{b} anomaly with Extra Vectors

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 on New Vector Bosons from Precision Electroweak Data

- EWPT place limits on *couplings/masses*
  Different dependence at hadron colliders!
- Leptonic couplings of new vectors small (LEP 2), or large masses
- Hadronic couplings can be large
- Cancellations of the effects of different new vectors can open new regions in parameter space
- Correlations with value of Higgs mass

Conclusions

LHC searches

Drell-Yan dilepton resonance $V \longrightarrow l\,l$ (neutral vectors)

- Only possible for $\mathcal{B}$ and $\mathcal{W}$
- Requires large enough lepton couplings
- EWPT + Tevatron $\longrightarrow$ Little space for discovery at 7 TeV
- Better at 14 TeV, 100 fb^{-1}

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

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

$V \longrightarrow jj$, $V \longrightarrow \bar{t}t$, $V \longrightarrow tb$, ...

- Required for leptophobic vector bosons
- Plenty of room for discovery

Pair production through gluon couplings

- Leptoquarks (decay via trilinear couplings)
- Exotic vectors without linear interactions

Thanks to

- Roberto & Paco
- All organizers
- All speakers
- All participants

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Good luck ProTevs !