Top anomalous couplings from effective operators: a minimal set

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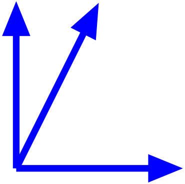
Introduction

A geometrical analogy

To parameterise the plane, two linearly independent vectors are sufficient

Three are too many, drop one!

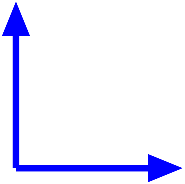


Introduction

A geometrical analogy

To parameterise the plane, two linearly independent vectors are sufficient

One can use an orthonormal basis …

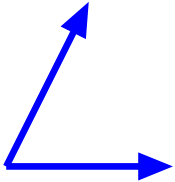


Introduction

A geometrical analogy

To parameterise the plane, two linearly independent vectors are sufficient

One can use a non-orthonomal one …



Introduction

A geometrical analogy

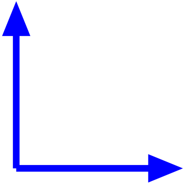
To parameterise the plane, two linearly independent vectors are sufficient

Results basis-independent …

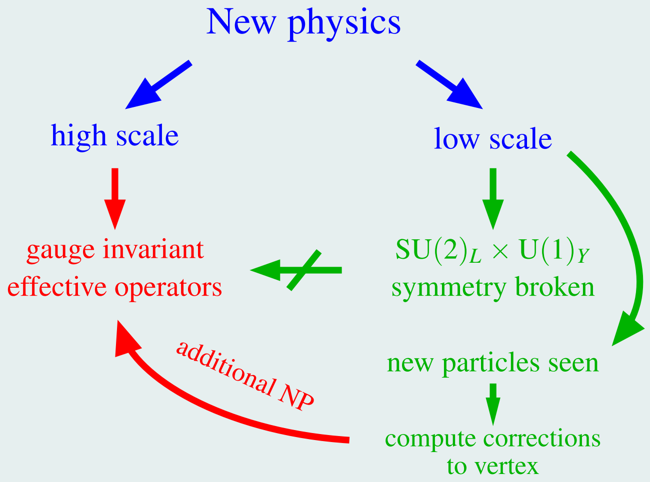
… but <u>amount of work</u> not!

Orthonormal basis easier for calculations

This talk: look for a minimal basis to parameterise top couplings



Effective operator approach to new physics corrections



Gauge-invariant effective operators

Many effective operators can be written in general

New physics contributions: some combination of them

Not all of them independent ➞ related by equations of motion for free fields

Important: the relations obtained from these equations are also valid for off-shell interactions [Georgi NPB '91 ...]

Huge effort to classify dim-6 effective operators removing redundant ones [Buchmuller, Wyler NPB '86]

☞ Most of work done ... but still some redundant!

Operators for top trilinear interactions

$$O_{\phi q}^{(3,ij)} = i(\phi^\dagger \tau^I D_\mu \phi)(\bar{q}_{Li} \gamma^\mu \tau^I q_{Lj})$$
$$O_{\phi q}^{(1,ij)} = i(\phi^\dagger D_\mu \phi)(\bar{q}_{Li} \gamma^\mu q_{Lj})$$
$$O_{\phi \phi}^{ij} = i(\tilde{\phi}^\dagger D_\mu \phi)(\bar{u}_{Ri} \gamma^\mu d_{Rj})$$
$$O_{\phi u}^{ij} = i(\phi^\dagger D_\mu \phi)(\bar{u}_{Ri} \gamma^\mu u_{Rj})$$
$$O_{uW}^{ij} = (\bar{q}_{Li} \sigma^{\mu\nu} \tau^I u_{Rj}) \tilde{\phi} \, W_{\mu\nu}^I$$
$$O_{dW}^{ij} = (\bar{q}_{Li} \sigma^{\mu\nu} \tau^I d_{Rj}) \phi \, W_{\mu\nu}^I$$
$$O_{uB\phi}^{ij} = (\bar{q}_{Li} \sigma^{\mu\nu} u_{Rj}) \tilde{\phi} \, B_{\mu\nu}$$
$$O_{uG\phi}^{ij} = (\bar{q}_{Li} \lambda^a \sigma^{\mu\nu} u_{Rj}) \tilde{\phi} \, G_{\mu\nu}^a$$
$$O_{u\phi}^{ij} = (\phi^\dagger \phi)(\bar{q}_{Li} u_{Rj} \tilde{\phi})$$

$$O_{Du}^{ij} = (\bar{q}_{Li} \, D_\mu u_{Rj}) \, D^\mu \, \tilde{\phi}$$
$$O_{\bar{D}u}^{ij} = (D_\mu \bar{q}_{Li} \, u_{Rj}) \, D^\mu \, \tilde{\phi}$$
$$O_{Dd}^{ij} = (\bar{q}_{Li} \, D_\mu d_{Rj}) \, D^\mu \, \phi$$
$$O_{\bar{D}d}^{ij} = (D_\mu \bar{q}_{Li} \, d_{Rj}) \, D^\mu \, \phi$$
$$O_{qW}^{ij} = \bar{q}_{Li} \gamma^\mu \tau^I D^\nu q_{Lj} W_{\mu\nu}^I$$
$$O_{qB}^{ij} = \bar{q}_{Li} \gamma^\mu D^\nu q_{Lj} B_{\mu\nu}$$
$$O_{uB}^{ij} = \bar{u}_{Ri} \gamma^\mu D^\nu u_{Rj} B_{\mu\nu}$$
$$O_{qG}^{ij} = \bar{q}_{Li} \lambda^a \gamma^\mu D^\nu q_{Lj} G_{\mu\nu}^a$$
$$O_{uG}^{ij} = \bar{u}_{Ri} \lambda^a \gamma^\mu D^\nu u_{Rj} G_{\mu\nu}^a$$

[Buchmuller, Wyler NPB '86]

Operators for top trilinear interactions

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$$O_{uG}^{ij} = \bar{u}_{Ri} \lambda^a \gamma^\mu D^\nu u_{Rj} G_{\mu\nu}^a$$

redundant

[Grzadkowski et al NPB '04]

Operators for top trilinear interactions

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redundant

[JAAS NPB '09]

Operators for top trilinear interactions

$$O_{\phi q}^{(3,i+j)} = i/2\,(\phi^\dagger (\tau^I D_\mu - \overleftarrow{D}_\mu \tau^I)\phi)(\bar q_{Li}\gamma^\mu \tau^I q_{Lj})$$
$$O_{\phi q}^{(1,i+j)} = i/2\,(\phi^\dagger \overleftrightarrow{D^\mu}\phi)(\bar q_{Li}\gamma^\mu q_{Lj})$$
$$O_{\phi\phi}^{ij} = i(\tilde\phi^\dagger D_\mu \phi)(\bar u_{Ri}\gamma^\mu d_{Rj})$$
$$O_{\phi u}^{i+j} = i/2\,(\phi^\dagger \overleftrightarrow{D^\mu}\phi)(\bar u_{Ri}\gamma^\mu u_{Rj})$$
$$O_{uW}^{ij} = (\bar q_{Li}\sigma^{\mu\nu}\tau^I u_{Rj})\tilde\phi\, W_{\mu\nu}^I$$
$$O_{dW}^{ij} = (\bar q_{Li}\sigma^{\mu\nu}\tau^I d_{Rj})\phi\, W_{\mu\nu}^I$$
$$O_{uB\phi}^{ij} = (\bar q_{Li}\sigma^{\mu\nu} u_{Rj})\tilde\phi\, B_{\mu\nu}$$
$$O_{uG\phi}^{ij} = (\bar q_{Li}\lambda^a\sigma^{\mu\nu} u_{Rj})\tilde\phi\, G_{\mu\nu}^a$$
$$O_{u\phi}^{ij} = (\phi^\dagger\phi)(\bar q_{Li} u_{Rj}\tilde\phi)$$

$$O_{Du}^{ij} = (\bar q_{Li} D_\mu u_{Rj})\, D^\mu\, \tilde\phi$$
$$O_{\bar D u}^{ij} = (D_\mu \bar q_{Li}\, u_{Rj})\, D^\mu\, \tilde\phi$$
$$O_{Dd}^{ij} = (\bar q_{Li} D_\mu d_{Rj})\, D^\mu\, \phi$$
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$$O_{uB}^{ij} = \bar u_{Ri}\gamma^\mu D^\nu u_{Rj} B_{\mu\nu}$$
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combinations $O_x^{ij} - (O_x^{ji})^\dagger$ redundant

[JAAS hep-ph '09]

But what means that operators are redundant?

They can be written as a linear combination of other operators already included in the list, using the equations of motion

Example #1:

$$O_{qW}^{ij} = -\frac{1}{4}\left[Y_{jk}^{u}\,O_{uW}^{ik} + Y_{jk}^{d}\,O_{dW}^{ik} - Y_{ki}^{u\dagger}\,(O_{uW}^{jk})^{\dagger} - Y_{ki}^{d\dagger}\,(O_{dW}^{jk})^{\dagger}\right] + \frac{g}{4}O_{\phi q}^{(3,i+j)}$$
$$+\frac{g}{4}(\bar{q}_{Li}\gamma^{\mu}\tau^{I}q_{Lj})(\bar{\ell}_{Lk}\gamma_{\mu}\tau^{I}\ell_{Lk}) + \frac{g}{4}(\bar{q}_{Li}\gamma^{\mu}\tau^{I}q_{Lj})(\bar{q}_{Lk}\gamma_{\mu}\tau^{I}q_{Lk})$$

Operators in blue were listed in the left column

(four-fermion terms not listed: they do not contribute to top couplings)

But what means that operators are redundant?

They can be written as a linear combination of other operators already included in the list, using the equations of motion

Example #2:

$$O_{\phi q}^{(3,ij)} - (O_{\phi q}^{(3,ji)})^\dagger \quad = \quad Y_{jk}^u O_{u\phi}^{ik} - Y_{jk}^d O_{d\phi}^{ik} - Y_{ki}^{u\dagger} (O_{u\phi}^{jk})^\dagger + Y_{ki}^{d\dagger} (O_{d\phi}^{jk})^\dagger$$

Not all i, j flavour combinations independent!

Instead of $O_{\phi q}^{(3,ij)}$ $\quad i,j = 1,2,3$

→ use $O_{\phi q}^{(3,i+j)} = \frac{1}{2}\left[O_{\phi q}^{(3,ij)} + (O_{\phi q}^{(3,ji)})^\dagger\right]$ $\quad i \leq j = 1,2,3$

and drop $O_{\phi q}^{(3,i-j)} = \frac{1}{2}\left[O_{\phi q}^{(3,ij)} - (O_{\phi q}^{(3,ji)})^\dagger\right]$ $\quad i \leq j = 1,2,3$

And can redundant operators just be dropped?

Certainly ☞ One can write any dim 6 operator in terms of the reduced "basis"

Many redundant operators already discarded in

[Buchmuller, Wyler NPB '86]

Using a redundant operator or an equivalent expression are two ways of writing (parameterising) the same quantity, up to dim 8 terms

The contributions to amplitudes are the same at this order (dim 6)

☞ Explicitly checked in several examples [JAAS NPB '08 '09]

And which is the "right" choice for the top quark?

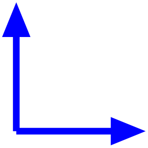
Dropping O^{ij}_{qW}, O^{ij}_{qG}, O^{ij}_{Du}, O^{ij}_{Dd}, ...

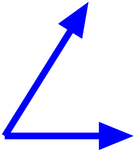
- top trilinear interactions are simplified
- several interesting process involve less diagrams

Dropping for example 4f operators

- many calculations (e.g. top decay) unchanged: 4f are not involved
- still lots of 4f operators remain, little improvement

See





A minimal set of top couplings

Wtb vertex

$$
\begin{aligned}
\mathcal{L}_{Wtb} \quad = \quad & -\frac{g}{\sqrt{2}}\, \bar{b}\, \gamma^{\mu} \left(V_L P_L + V_R P_R \right) t\, W_{\mu}^{-} \\
& -\frac{g}{\sqrt{2}}\, \bar{b}\, \frac{i\sigma^{\mu\nu} q_{\nu}}{M_W} \left(g_L P_L + g_R P_R \right) t\, W_{\mu}^{-} \\
& -\frac{g}{\sqrt{2}}\, \bar{b} \left[\frac{q^{\mu}}{M_W} (f_{1L} P_L + f_{1R} P_R) + \frac{k^{\mu}}{M_W} (f_{2L} P_L + f_{2R} P_R) \right] t\, W_{\mu}^{-} \\
& -\frac{g}{\sqrt{2}}\, \frac{q^2}{M_W^2}\, \bar{b}\, \gamma^{\mu} \xi_L^W P_L\, t\, W_{\mu}^{-} \\
& -\frac{g}{\sqrt{2}}\, \frac{1}{M_W^2}\, \bar{b} (\not{q} k^{\mu} - k \cdot q\, \gamma^{\mu}) h_L^W P_L\, t\, W_{\mu}^{-} + \text{h.c.}
\end{aligned}
$$

A minimal set of top couplings

Wtb vertex

More

$$
\begin{aligned}
\mathcal{L}_{Wtb} = & -\frac{g}{\sqrt{2}} \bar{b} \gamma^\mu (V_L P_L + V_R P_R) t W_\mu^- \\
& -\frac{g}{\sqrt{2}} \bar{b} \frac{i\sigma^{\mu\nu} q_\nu}{M_W} (g_L P_L + g_R P_R) t W_\mu^- + \text{h.c.} \\
& -\frac{g}{\sqrt{2}} \bar{b} \left[\frac{q^\mu}{M_W} (f_{1L} P_L + f_{1R} P_R) + \frac{k^\mu}{M_W} (f_{2L} P_L + f_{2R} P_R) \right] t W_\mu^- \\
& -\frac{g}{\sqrt{2}} \frac{q^2}{M_W^2} \bar{b} \gamma^\mu \xi_L^W P_L t W_\mu^- \\
& -\frac{g}{\sqrt{2}} \frac{1}{M_W^2} \bar{b} (\not{q} k^\mu - k \cdot q \gamma^\mu) h_L^W P_L t W_\mu^- + \text{h.c.}
\end{aligned}
$$

A minimal set of top couplings

Ztt vertex

$$
\begin{aligned}
\mathcal{L}_{Ztt} \;=\; & -\frac{g}{2c_W}\,\bar{t}\,\gamma^\mu\left(X_{tt}^L P_L + X_{tt}^R P_R - 2s_W^2 Q_t\right) t\, Z_\mu \\
& -\frac{g}{2c_W}\,\bar{t}\,\frac{i\sigma^{\mu\nu}q_\nu}{M_Z}\left(d_V^Z + i d_A^Z \gamma_5\right) t\, Z_\mu \\
& -\frac{g}{2c_W}\,\bar{t}\left[\frac{q^\mu}{M_Z}(f_{1L}^Z P_L + f_{1R}^Z P_R) + \frac{k^\mu}{M_Z}(f_{2L}^Z P_L + f_{2R}^Z P_R)\right] t\, Z_\mu \\
& -\frac{g}{2c_W}\frac{q^2}{M_Z^2}\,\bar{t}\,\gamma^\mu(\xi_L^Z P_L + \xi_R^Z P_R)\, t\, Z_\mu \\
& -\frac{g}{2c_W}\frac{1}{M_Z^2}\,\bar{t}(\not{q} k^\mu - k\cdot q\;\gamma^\mu)(h_L^Z P_L + h_R^Z P_R)\, t\, Z_\mu
\end{aligned}
$$

A minimal set of top couplings

Ztt vertex

More

$$\begin{aligned}\mathcal{L}_{Ztt} = & -\frac{g}{2c_W}\bar{t}\gamma^\mu\left(X_{tt}^L P_L + X_{tt}^R P_R - 2s_W^2 Q_t\right) t\, Z_\mu \\ & -\frac{g}{2c_W}\bar{t}\frac{i\sigma^{\mu\nu}q_\nu}{M_Z}\left(d_V^Z + i d_A^Z \gamma_5\right) t\, Z_\mu \\ & -\frac{g}{2c_W}\bar{t}\left[\frac{q^\mu}{M_Z}(f_{1L}^Z P_L + f_{1R}^Z P_R) + \frac{k^\mu}{M_Z}(f_{2L}^Z P_L + f_{2R}^Z P_R)\right] t\, Z_\mu \\ & -\frac{g}{2c_W}\frac{q^2}{M_Z^2}\bar{t}\gamma^\mu(\xi_L^Z P_L + \xi_R^Z P_R) t\, Z_\mu \\ & -\frac{g}{2c_W}\frac{1}{M_Z^2}\bar{t}(\not{q} k^\mu - k\cdot q\,\gamma^\mu)(h_L^Z P_L + h_R^Z P_R) t\, Z_\mu\end{aligned}$$

A minimal set of top couplings

γtt vertex

$$\begin{aligned}
\mathcal{L}_{\gamma tt} &= -eQ_t \bar{t}\gamma^\mu t\, A_\mu - e\,\bar{t}\,\frac{i\sigma^{\mu\nu}q_\nu}{m_t}\,(d_V^\gamma + i d_A^\gamma \gamma_5)\, t\, A_\mu \\
&\quad - e\,\frac{q^2}{m_t^2}\bar{t}\,\gamma^\mu(\xi_L^\gamma P_L + \xi_R^\gamma P_R)\, t\, A_\mu \\
&\quad - e\,\frac{1}{m_t^2}\bar{t}(\not{q} k^\mu - k\cdot q\,\gamma^\mu)(h_L^\gamma P_L + h_R^\gamma P_R)\, t\, A_\mu
\end{aligned}$$

A minimal set of top couplings

γtt vertex

More

$$\mathcal{L}_{\gamma tt} = -eQ_t\bar{t}\gamma^\mu t\, A_\mu - e\,\bar{t}\,\frac{i\sigma^{\mu\nu}q_\nu}{m_t}\left(d_V^\gamma + i d_A^\gamma \gamma_5\right) t\, A_\mu$$

$$- e\,\frac{q^2}{m_t^2}\bar{t}\,\gamma^\mu\left(\xi_L^\gamma P_L + \xi_R^\gamma P_R\right) t\, A_\mu$$

$$- e\,\frac{1}{m_t^2}\bar{t}\left(\not{q} k^\mu - k\cdot q\,\gamma^\mu\right)\left(h_L^\gamma P_L + h_R^\gamma P_R\right) t\, A_\mu$$

A minimal set of top couplings

gtt vertex

$$
\begin{aligned}
\mathcal{L}_{gtt} \;=\;& -g_s \bar{t} \frac{\lambda^a}{2} \gamma^\mu t \, G_\mu^a - g_s \, \bar{t} \lambda^a \, \frac{i\sigma^{\mu\nu} q_\nu}{m_t} \left(d_V^g + i d_A^g \gamma_5 \right) t \, G_\mu^a \\
& - g_s \, \frac{q^2}{m_t^2} \bar{t} \, \lambda^a \gamma^\mu \left(\xi_L^g P_L + \xi_R^g P_R \right) t \, G_\mu^a \\
& - g_s \, \frac{1}{m_t^2} \bar{t} \, \lambda^a \left(\not{q} k^\mu - k \cdot q \, \gamma^\mu \right) \left(h_L^g P_L + h_R^g P_R \right) t \, G_\mu^a
\end{aligned}
$$

A minimal set of top couplings

gtt vertex

More

$$\mathcal{L}_{gtt} = -g_s \bar{t} \frac{\lambda^a}{2} \gamma^\mu t \, G^a_\mu - g_s \, \bar{t} \lambda^a \, \frac{i\sigma^{\mu\nu} q_\nu}{m_t} \left(d_V^g + i d_A^g \gamma_5 \right) t \, G^a_\mu$$

$$- g_s \, \frac{q^2}{m_t^2} \bar{t} \, \lambda^a \gamma^\mu (\xi_L^g P_L + \xi_R^g P_R) \, t \, G^a_\mu$$

$$- g_s \, \frac{1}{m_t^2} \bar{t} \, \lambda^a (\not{q} k^\mu - k \cdot q \, \gamma^\mu)(h_L^g P_L + h_R^g P_R) \, t \, G^a_\mu$$

A minimal set of top couplings

Htt vertex

$$
\begin{aligned}
\mathcal{L}_{Htt} &= -\frac{1}{\sqrt{2}} \bar{t} \left(Y_t^V + i Y_t^A \gamma_5 \right) t\, H \\
&\quad - \frac{1}{\sqrt{2}} \frac{q_\mu}{m_t} \bar{t} \gamma^\mu \left(\omega_{tt}^L P_L + \omega_{tt}^R P_R \right) t\, H
\end{aligned}
$$

A minimal set of top couplings

Htt vertex

More

$$\mathcal{L}_{Htt} = -\frac{1}{\sqrt{2}} \bar{t} \left(Y_t^V + i Y_t^A \gamma_5 \right) t\, H$$

$$- \frac{1}{\sqrt{2}} \frac{q_\mu}{m_t} \bar{t} \gamma^\mu \left(\omega_{tt}^L P_L + \omega_{tt}^R P_R \right) t\, H$$

A minimal set of top couplings

Ztc vertex — Ztu similar

$$
\begin{aligned}
\mathcal{L}_{Ztc} \quad = \quad & -\frac{g}{2c_W}\,\bar{c}\,\gamma^\mu\left(X_{ct}^L P_L + X_{ct}^R P_R\right) t\, Z_\mu \\
& -\frac{g}{2c_W}\,\bar{c}\,\frac{i\sigma^{\mu\nu}q_\nu}{M_Z}\left(\kappa_{ct}^L P_L + \kappa_{ct}^R P_R\right) t\, Z_\mu \\
& -\frac{g}{2c_W}\,\bar{c}\left[\frac{q^\mu}{M_Z}(f_{1L}^{ct} P_L + f_{1R}^{ct} P_R) + \frac{k^\mu}{M_Z}(f_{2L}^{ct} P_L + f_{2R}^{ct} P_R)\right] t\, Z_\mu \\
& -\frac{g}{2c_W}\,\frac{q^2}{M_Z^2}\,\bar{c}\,\gamma^\mu(\beta_L^Z P_L + \beta_R^Z P_R)\, t\, Z_\mu \\
& -\frac{g}{2c_W}\,\frac{1}{M_Z^2}\,\bar{c}(\not{q} k^\mu - k\cdot q\,\gamma^\mu)(\theta_L^Z P_L + \theta_R^Z P_R)\, t\, Z_\mu + \text{h.c.}
\end{aligned}
$$

A minimal set of top couplings

Ztc vertex — Ztu similar

More

$$
\begin{aligned}
\mathcal{L}_{Ztc} = & -\frac{g}{2c_W}\,\bar{c}\,\gamma^\mu\left(X_{ct}^L P_L + X_{ct}^R P_R\right) t\, Z_\mu \\
& -\frac{g}{2c_W}\,\bar{c}\,\frac{i\sigma^{\mu\nu}q_\nu}{M_Z}\left(\kappa_{ct}^L P_L + \kappa_{ct}^R P_R\right) t\, Z_\mu + \text{h.c.} \\
& -\frac{g}{2c_W}\,\bar{c}\left[\frac{q^\mu}{M_Z}(f_{1L}^{ct} P_L + f_{1R}^{ct} P_R) + \frac{k^\mu}{M_Z}(f_{2L}^{ct} P_L + f_{2R}^{ct} P_R)\right] t\, Z_\mu \\
& -\frac{g}{2c_W}\,\frac{q^2}{M_Z^2}\,\bar{c}\,\gamma^\mu(\beta_L^Z P_L + \beta_R^Z P_R)\, t\, Z_\mu \\
& -\frac{g}{2c_W}\,\frac{1}{M_Z^2}\,\bar{c}(\not{q} k^\mu - k\cdot q\,\gamma^\mu)(\theta_L^Z P_L + \theta_R^Z P_R)\, t\, Z_\mu + \text{h.c.}
\end{aligned}
$$

A minimal set of top couplings

γtc vertex — γtu similar

$$
\begin{aligned}
\mathcal{L}_{\gamma tc} \quad = \quad & -e\,\bar{c}\,\frac{i\sigma^{\mu\nu}q_\nu}{m_t}\left(\lambda_{ct}^L P_L + \lambda_{ct}^R P_R\right) t\, A_\mu \\
& - e\,\frac{q^2}{m_t^2}\bar{c}\,\gamma^\mu(\beta_L^\gamma P_L + \beta_R^\gamma P_R)\,t\,A_\mu \\
& - e\,\frac{1}{m_t^2}\bar{c}(\not{q}k^\mu - k\cdot q\,\gamma^\mu)(\theta_L^\gamma P_L + \theta_R^\gamma P_R)\,t\,A_\mu + \text{h.c.}
\end{aligned}
$$

A minimal set of top couplings

γtc vertex — γtu similar

More

$$\mathcal{L}_{\gamma tc} = -e\,\bar{c}\,\frac{i\sigma^{\mu\nu}q_\nu}{m_t}\left(\lambda_{ct}^L P_L + \lambda_{ct}^R P_R\right) t\,A_\mu + \text{h.c.}$$

$$- e\,\frac{q^2}{m_t^2}\bar{c}\,\gamma^\mu(\beta_L^\gamma P_L + \beta_R^\gamma P_R)\,t\,A_\mu$$

$$- e\,\frac{1}{m_t^2}\bar{c}(\not{q}k^\mu - k\cdot q\,\gamma^\mu)(\theta_L^\gamma P_L + \theta_R^\gamma P_R)\,t\,A_\mu + \text{h.c.}$$

A minimal set of top couplings

gtc vertex — *gtu* similar

$$\begin{aligned}\mathcal{L}_{gtc} = & -g_s\,\bar{c}\,\lambda^a \frac{i\sigma^{\mu\nu} q_\nu}{m_t} \left(\zeta_{ct}^L P_L + \zeta_{ct}^R P_R\right) t\, G_\mu^a \\ & - g_s\,\frac{q^2}{m_t^2} \bar{c}\,\lambda^a \gamma^\mu (\beta_L^g P_L + \beta_R^g P_R)\, t\, G_\mu^a \\ & - e\,\frac{1}{m_t^2} \bar{c}\,\lambda^a (\not{q} k^\mu - k \cdot q\, \gamma^\mu)(\theta_L^g P_L + \theta_R^g P_R)\, t\, G_\mu^a + \text{h.c.}\end{aligned}$$

A minimal set of top couplings

gtc vertex — *gtu* similar

More

$$\mathcal{L}_{gtc} = -g_s \, \bar c \, \lambda^a \frac{i\sigma^{\mu\nu} q_\nu}{m_t} \left(\zeta_{ct}^L P_L + \zeta_{ct}^R P_R \right) t \, G_\mu^a + \text{h.c.}$$

$$- g_s \frac{q^2}{m_t^2} \bar c \, \lambda^a \gamma^\mu (\beta_L^g P_L + \beta_R^g P_R) \, t \, G_\mu^a$$

$$- e \frac{1}{m_t^2} \bar c \, \lambda^a (\not{q} k^\mu - k \cdot q \, \gamma^\mu)(\theta_L^g P_L + \theta_R^g P_R) \, t \, G_\mu^a + \text{h.c.}$$

A minimal set of top couplings

Htc vertex — *Htu* similar

$$\mathcal{L}_{Htc} = -\frac{1}{\sqrt{2}} \bar{c} \left(\eta^L_{ct} P_L + \eta^R_{ct} P_R \right) t \, H - \frac{1}{\sqrt{2}} \frac{q_\mu}{m_t} \bar{c} \, \gamma^\mu \left(\omega^L_{ct} P_L + \omega^R_{ct} P_R \right) t \, H + \text{h.c.}$$

A minimal set of top couplings

Htc vertex — *Htu* similar

More

$$\mathcal{L}_{Htc} = -\frac{1}{\sqrt{2}} \bar{c} \left(\eta^L_{ct} P_L + \eta^R_{ct} P_R \right) t \, H + \text{h.c.}$$

$$- \frac{1}{\sqrt{2}} \frac{q_\mu}{m_t} \bar{c} \gamma^\mu \left(\omega^L_{ct} P_L + \omega^R_{ct} P_R \right) t \, H + \text{h.c.}$$

In summary:

① Gauge interactions: only γ^μ and $\sigma^{\mu\nu} q_\nu$ terms

② Higgs: only scalar and pseudo-scalar terms

☞ This is of course valid for any fermion not only the top quark!

This simplifies [phenomenological analyses / Monte Carlo building]

Q & A:

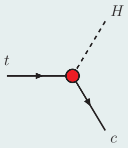
Q: Why is this new? I've been using only γ^μ and $\sigma^{\mu\nu} q_\nu$ all my life!

A: Yes, but possibly you were using top on-shell. This is valid for top off-shell, light quarks off-shell and bosons off-shell

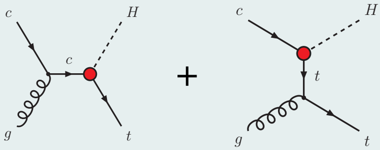
Simplification for analyses

Top-charm-Higgs vertex with redundant operators

$$\mathcal{L}_{Htc} = -\frac{1}{\sqrt{2}}\,\bar{c}\left(\eta^L_{ct} P_L + \eta^R_{ct} P_R\right) t\, H - \frac{1}{\sqrt{2}}\frac{q_\mu}{m_t}\,\bar{c}\,\gamma^\mu \left(\omega^L_{ct} P_L + \omega^R_{ct} P_R\right) t\, H$$



$$\Gamma = A\left[|\eta^L_{ct} + \omega^R_{ct}|^2 + |\eta^R_{ct} + \omega^L_{ct}|^2\right]$$



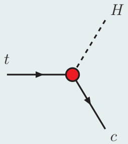
$$\sigma = B\left[|\eta^L_{ct} + \omega^R_{ct}|^2 + |\eta^R_{ct} + \omega^L_{ct}|^2\right]$$

Suspicious coincidence ... ω vertex is q-dependent!

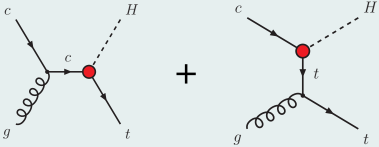
Simplification for analyses

Minimal top-charm-Higgs vertex

$$\mathcal{L}_{Htc} = -\frac{1}{\sqrt{2}}\,\bar{c}\left(\eta^L_{ct} P_L + \eta^R_{ct} P_R\right) t\, H - \frac{1}{\sqrt{2}}\frac{q_\mu}{m_t}\,\bar{c}\,\gamma^\mu \left(\omega^L_{ct} P_L + \omega^R_{ct} P_R\right) t\, H$$



$$\Gamma = A\left[|\eta^L_{ct}|^2 + |\eta^R_{ct}|^2\right]$$



$$\sigma = B\left[|\eta^L_{ct}|^2 + |\eta^R_{ct}|^2\right]$$

4 parameters $\to$ 2 parameters

Q & A:

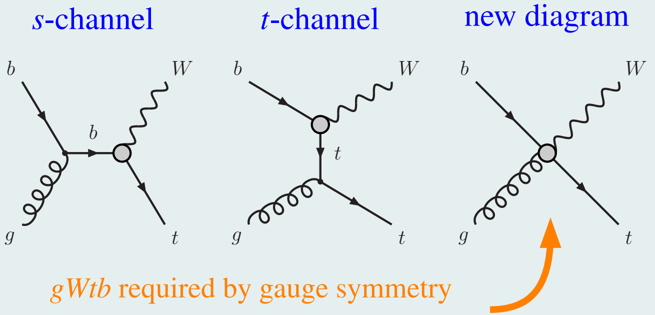
Q: And what's wrong with having a few extra parameters?

A: If you rename a single parameter 'a' as '$b + c$', you will not measure b nor c individually with your observables, which all depend on $b + c$

Simplification for Monte Carlos

Vertices simpler, and amplitudes also involve less diagrams

Example: tW^- production with Wtb anomalous couplings



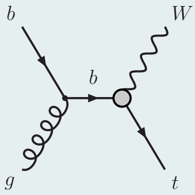
$gWtb$ required by gauge symmetry
if redundant operators included

Simplification for Monte Carlos

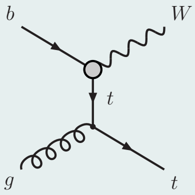
Vertices simpler, and amplitudes also involve less diagrams

Example: tW^- production with Wtb anomalous couplings

s-channel



t-channel



new diagram
not needed

Equivalent parameterisations of the same new physics

One can either

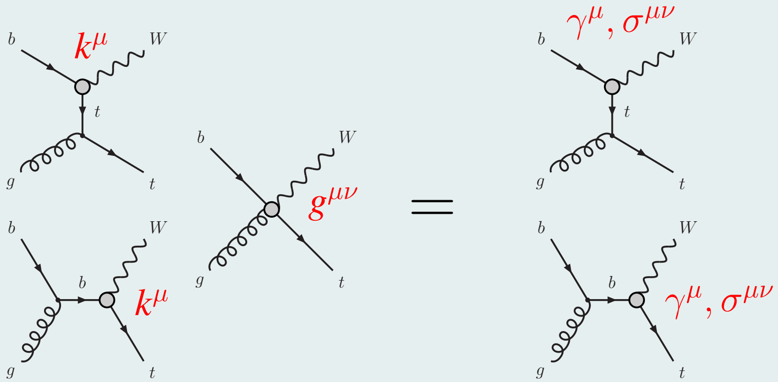
- Use for example O_{Du}^{ij}, which involves new Wtb couplings and an associated $gWtb$ vertex

  ➡ The extra diagram with the quartic vertex must appear

- Replace O_{Du}^{ij} by an equivalent expression (up to dim 8) which for Wtb involves γ^μ, $\sigma^{\mu\nu}$ already present from other operators and does not have any $gWtb$ vertex

  ➡ The contribution to the amplitudes is the same but the parameterisation is much simpler

Gauge invariance in a picture



Implementation: Protos and TopFit

Top interactions tested at LHC involve general off-shell vertices

- Single top tW: Wtb with t / b off-shell
- $t\bar{t}Z$: Ztt with one t off-shell
- $t\bar{t}\gamma$: γtt with one t off-shell
- Zt production: Ztc with t / c off-shell
- γt production: γtc with t / c off-shell
- …

☞ Here the effort to obtain a minimal set of operators pays off: description completely general but much simpler

Monte Carlo implementation: Protos

Generator `Protos` (PROgram for TOp Simulations) for

1. Single top and $t\bar{t}$ production with anomalous *Wtb* couplings
2. Top FCNC production and decay
3. Some exotics

Includes the minimal sets of top anomalous couplings arising from dim 6 effective operators

Monte Carlo implementation: Protos

General features

- ★ Matrix elements calculated with HELAS
- ★ Top and W off-shell (Breit-Wigner resonances)
- ★ Spin information kept in decay chain
- ★ Integration done with VEGAS
- ★ Many numerical outputs (checks) provided: W helicity fractions, angular asymmetries, $t\bar{t}$ spin correlations …
- ★ ATLAS interface ready, waiting for CMS

Monte Carlo implementation: Protos

Protos for *Wtb* anomalous couplings

The generator includes:

- single top in all channels, with double counting removal
- top pair production

Event samples with *Wtb* anomalous couplings necessary for several LHC analyses See

1. Limits on anomalous *Wtb* couplings from single top
2. *W* helicity measurements with templates

Monte Carlo implementation: Protos

Protos for top FCNC processes

The generator includes:

- single top: $pp \to Zt/\gamma t/t/Ht$
- top pair production with $t \to Zq/\gamma q/gq/Hq$

Simulated event samples for these processes necessary to compare with data and extract limits on top rare decays

Obtaining limits: TopFit

After the reduction in the number of meaningful parameters, we can obtain model-independent measurements and limits

(or with very few assumptions)

Example: *Wtb* vertex

$$\begin{aligned} \mathcal{L}_{Wtb} &= -\frac{g}{\sqrt{2}}\,\bar{b}\,\gamma^{\mu}\left(V_L P_L + V_R P_R\right) t\; W_\mu^- \\ &\quad -\frac{g}{\sqrt{2}}\,\bar{b}\,\frac{i\sigma^{\mu\nu} q_\nu}{M_W}\left(g_L P_L + g_R P_R\right) t\; W_\mu^- + \text{h.c.} \end{aligned}$$

$$q = p_t - p_b = p_W$$

Approaches to measurement of *Wtb* couplings

1. Perform model-dependent measurements

   Example: measure V_{tb} in single top production assuming all *Wtb* anomalous couplings zero

2. Perform model-independent measurements assuming a general Lagrangian and performing a fit with all known data

   - ★ either we find *Wtb* anomalous couplings
   - ★ or we clean the room to see NP in production

☞ Rohini's talk

Anomalous *Wtb* couplings and top observables

1. Single top cross sections

   $$\sigma = \sigma_{\rm SM} \left(V_L^2 + \kappa^{V_R} V_R^2 + \kappa^{V_L V_R} V_L V_R + \kappa^{g_L} g_L^2 + \kappa^{g_R} g_R^2 + \dots \right)$$

2. W helicity observables in $t \to Wb \to \ell \nu b$

   helicity fractions F_R, F_L, F_0 and ratios $\rho_{R,L}$

   angular asymmetries $A_\pm$ … ▸ See

3. Spin asymmetries in single and pair production

   single top: A_b, A_ℓ … top pair: A_{ll}, $A_{\ell j}$ … ▸ See

4. Their ratios, independent of production mechanism

   $$r_{bl} = \frac{A_b}{A_\ell} = \frac{A_{bj}}{A_{\ell j}}\,, \quad r_{\nu l}, \quad \dots$$ ▸ See

The global fit to the *Wtb* vertex

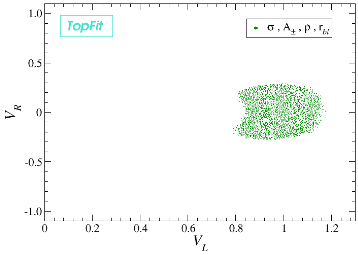
An example: the input

- Exact expressions for W helicity ratios and spin analysing powers in top decay $t \to Wb \to f f' b$
- Their expected ATLAS precision with 10 fb^{-1}
- Expressions for single top xsec with anomalous couplings including theoretical uncertainty
- Expected ATLAS precision for tW xsec with 30 fb^{-1}
- CP conservation assumed: couplings taken real

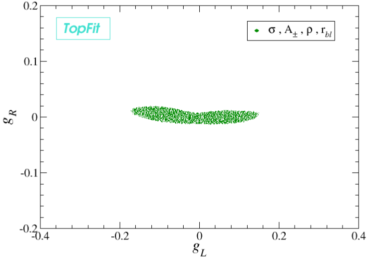
The global fit to the *Wtb* vertex

An example: the output

(V_L, V_R) projection



(g_L, g_R) projection



Many cancellations possible in single observables ➙ life is not easy

All of them allowed in the fit ➙ reduced by combination

Almost model-independent measurement of V_{tb} (assuming CP)

Implications for spin correlations

Measurement of C, D in the dilepton channel [Hubaut et al. EPJC '05]

Invariant mass cut: $m_{t\bar{t}} < 550$ GeV to increase C, D

Extraction of C, D from asymmetries: $C = \frac{4\,A_{\ell\ell}}{\alpha_\ell^2} \quad D = \frac{2\,\tilde{A}_{\ell\ell}}{\alpha_\ell^2}$

➞ Uncertainty from α due to anomalous couplings

Uncertainties in SM

$$C = 0.404 \pm 0.020\ (\text{stat}) \pm 0.024\ (\text{sys})$$
$$D = -0.290 \pm 0.011\ (\text{stat}) \pm 0.010\ (\text{sys})$$

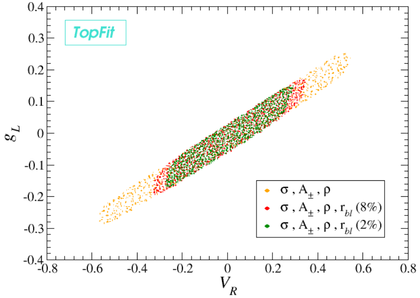
Uncertainty from α

$$C = [0.404 - 0.461]$$
$$D = -[0.290 - 0.331]$$

☞ Need more precision in *Wtb* couplings!

Work for the future

Main limitation: $V_R - g_L$ cancellation in $A_\pm$, $\rho_{R,L}$



r_{bl} crucial to improve limits but only up to some point

☞ More observables required!

Conclusion

★ Fermion trilinear interactions arising from dim 6 gauge-invariant effective operators are simpler than expected

- γ^μ, $\sigma^{\mu\nu} q_\nu$ terms for gauge bosons
- scalar and pseudo-scalar for the Higgs

★ This is the minimal structure: if more operators are found redundant it will not be simplified further

★ Dropping one operator or another is a matter of taste, but our choice seems simpler for top phenomenology

Conclusion

Program to have limits on top anomalous couplings

Conclusion

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① To know exactly the Lagrangian, minimal but general ✔

(that is, to know which the anomalous couplings are)

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② Generators involving top anomalous couplings ✔
(`Protos`)

Conclusion

Program to have limits on top anomalous couplings

1. To know exactly the Lagrangian, minimal but general ✔
   (that is, to know which the anomalous couplings are)
2. Generators involving top anomalous couplings ✔
   (`Protos`)
3. Correct theoretical expressions for observables ✔

Conclusion

Program to have limits on top anomalous couplings

1. To know exactly the Lagrangian, minimal but general ✔
   (that is, to know which the anomalous couplings are)
2. Generators involving top anomalous couplings ✔
   (`Protos`)
3. Correct theoretical expressions for observables ✔
4. A program to fit the data ✔
   (`TopFit`)

Conclusion

Program to have limits on top anomalous couplings

1. To know exactly the Lagrangian, minimal but general ✔
   (that is, to know which the anomalous couplings are)
2. Generators involving top anomalous couplings ✔
   (`Protos`)
3. Correct theoretical expressions for observables ✔
4. A program to fit the data ✔
   (`TopFit`)
5. The data itself . . . ✘

Four-fermion operators contributing to single top (t, s-channel)
(i, j, k, l are flavour indices) [Buchmuller, Wyler NPB '86]

$(\bar{q}_{Li}\gamma_\mu q_{Lj})(\bar{q}_{Lk}\gamma^\mu q_{Ll})$	$(\bar{q}_{Li}\gamma_\mu \lambda^a q_{Lj})(\bar{q}_{Lk}\gamma^\mu \lambda^a q_{Ll})$
$(\bar{q}_{Li}\gamma_\mu \tau^I q_{Lj})(\bar{q}_{Lk}\gamma^\mu \tau^I q_{Ll})$	$(\bar{q}_{Li}\gamma_\mu \lambda^a \tau^I q_{Lj})(\bar{q}_{Lk}\gamma^\mu \lambda^a \tau^I q_{Ll})$
$(\bar{u}_{Ri}\gamma_\mu u_{Rj})(\bar{d}_{Rk}\gamma^\mu d_{Rl})$	$(\bar{u}_{Ri}\gamma_\mu \lambda^a u_{Rj})(\bar{d}_{Rk}\gamma^\mu \lambda^a d_{Rl})$
$(\bar{q}_{Li} u_{Rj})(\bar{u}_{Rk} q_{Ll})$	$(\bar{q}_{Li}\lambda^a u_{Rj})(\bar{u}_{Rk}\lambda^a q_{Ll})$
$(\bar{q}_{Li} d_{Rj})(\bar{d}_{Rk} q_{Ll})$	$(\bar{q}_{Li}\lambda^a d_{Rj})(\bar{d}_{Rk}\lambda^a q_{Ll})$
$(\bar{q}_{Li} u_{Rj})([\bar{q}_{Lk}\epsilon]^T d_{Rl})$	$(\bar{q}_{Li}\lambda^a u_{Rj})([\bar{q}_{Lk}\epsilon]^T \lambda^a d_{Rl})$

12 for $ub \to dt$
12 for $cb \to st$
➞ total = 24 operators

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Contributions to *Wtb* vertex

$$\delta V_L = C_{\phi q}^{(3,3+3)*} \frac{v^2}{\Lambda^2} \qquad \delta g_L = \sqrt{2} C_{dW}^{33*} \frac{v^2}{\Lambda^2}$$

$$\delta V_R = \frac{1}{2} C_{\phi\phi}^{33} \frac{v^2}{\Lambda^2} \qquad \delta g_R = \sqrt{2} C_{uW}^{33} \frac{v^2}{\Lambda^2}$$

Back

Contributions to *Ztt* vertex

$$\delta X_{tt}^{L} = \left[C_{\phi q}^{(3,3+3)} - C_{\phi q}^{(1,3+3)} \right] \frac{v^2}{\Lambda^2}$$

$$\delta X_{tt}^{R} = - C_{\phi u}^{3+3} \frac{v^2}{\Lambda^2}$$

$$\delta d_V^Z = \sqrt{2}\,\mathrm{Re}\,\left[c_W C_{uW}^{33} - s_W C_{uB\phi}^{33} \right] \frac{v^2}{\Lambda^2}$$

$$\delta d_A^Z = \sqrt{2}\,\mathrm{Im}\,\left[c_W C_{uW}^{33} - s_W C_{uB\phi}^{33} \right] \frac{v^2}{\Lambda^2}$$

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Contributions to γtt vertex

$$\delta d_V^\gamma = \frac{\sqrt{2}}{e} \mathrm{Re} \left[c_W C_{uB\phi}^{33} + s_W C_{uW}^{33} \right] \frac{v m_t}{\Lambda^2}$$

$$\delta d_A^\gamma = \frac{\sqrt{2}}{e} \mathrm{Im} \left[c_W C_{uB\phi}^{33} + s_W C_{uW}^{33} \right] \frac{v m_t}{\Lambda^2}$$

Back

Contributions to *gtt* vertex

$$\delta d_V^g = \frac{\sqrt{2}}{g_s} \mathrm{Re}\, C_{uG\phi}^{33} \frac{v m_t}{\Lambda^2}$$

$$\delta d_A^g = \frac{\sqrt{2}}{g_s} \mathrm{Im}\, C_{uG\phi}^{33} \frac{v m_t}{\Lambda^2}$$

Back

Contributions to *Htt* vertex

$$\delta Y_t^V = -\frac{3}{2}\,\mathrm{Re}\,C_{u\phi}^{33}\,\frac{v^2}{\Lambda^2}$$
$$\delta Y_t^A = -\frac{3}{2}\,\mathrm{Im}\,C_{u\phi}^{33}\,\frac{v^2}{\Lambda^2}$$

Back

Contributions to *Ztc* vertex

$$\delta X_{ct}^{L} = \frac{1}{2}\left[C_{\phi q}^{(3,2+3)} - C_{\phi q}^{(1,2+3)}\right]\frac{v^2}{\Lambda^2}$$

$$\delta X_{ct}^{R} = -\frac{1}{2}\left[C_{\phi u}^{2+3}\right]\frac{v^2}{\Lambda^2}$$

$$\delta \kappa_{ct}^{L} = \sqrt{2}\left[c_W C_{uW}^{32*} - s_W C_{uB\phi}^{32*}\right]\frac{v^2}{\Lambda^2}$$

$$\delta \kappa_{ct}^{R} = \sqrt{2}\left[c_W C_{uW}^{23} - s_W C_{uB\phi}^{23}\right]\frac{v^2}{\Lambda^2}$$

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Contributions to γtc vertex

$$\delta\lambda_{ct}^{L} = \frac{\sqrt{2}}{e}\left[s_W C_{uW}^{32*} + c_W C_{uB\phi}^{32*}\right]\frac{vm_t}{\Lambda^2}$$
$$\delta\lambda_{ct}^{R} = \frac{\sqrt{2}}{e}\left[s_W C_{uW}^{23} + c_W C_{uB\phi}^{23}\right]\frac{vm_t}{\Lambda^2}$$

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Contributions to *gtc* vertex

$$\delta\zeta_{ct}^{L} = \frac{\sqrt{2}}{g_s} C_{uG\phi}^{32*} \frac{v m_t}{\Lambda^2}$$

$$\delta\zeta_{ct}^{R} = \frac{\sqrt{2}}{g_s} C_{uG\phi}^{23} \frac{v m_t}{\Lambda^2}$$

Back

Contributions to *Htc* vertex

$$\delta\eta^L_{ct} = -\frac{3}{2}\, C^{32*}_{u\phi}\, \frac{v^2}{\Lambda^2}$$

$$\delta\eta^R_{ct} = -\frac{3}{2}\, C^{23}_{u\phi}\, \frac{v^2}{\Lambda^2}$$

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Testing efficiency variations with anomalous couplings

When limits on *Wtb* anomalous couplings are extracted from total cross sections the efficiency variations must be taken into account

$\sigma^{\mu\nu}$ couplings affect kinematics → affect efficiency

This can be done by extracting limits for SM efficiency and testing the variations within the limits obtained [JAAS NPB '08]

☞ Samples required with anomalous couplings

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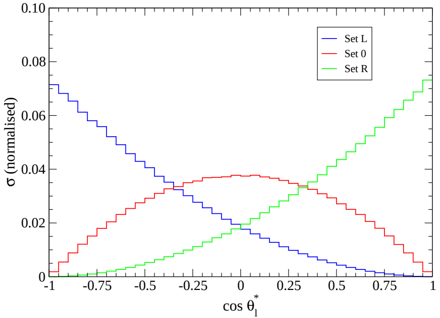
Generating templates for W helicities



- Single t: anomalous couplings switched off in production or decay
- $t\bar{t}$: independent templates for hadronic and leptonic top

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Parameters

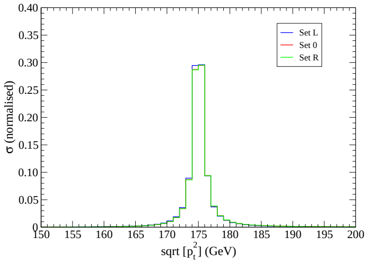
Set L:
$$V_L \simeq -0.4917$$
$$V_R = 0$$
$$g_L \simeq 0$$
$$g_R \simeq -1.069$$

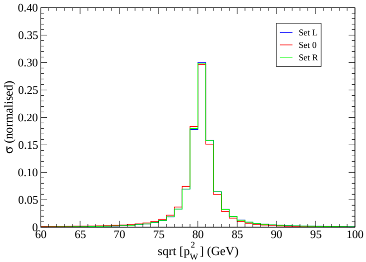
Set 0:
$$V_L \simeq 1.513$$
$$V_R = 0$$
$$g_L \simeq -0.0191$$
$$g_R \simeq 0.6956$$

Set R:
$$V_L = 0$$
$$V_R \simeq 0.4917$$
$$g_L \simeq 1.069$$
$$g_R \simeq 0$$

Generating templates for W helicities

Top and W boson invariant mass keep Breit-Wigner shape in all cases





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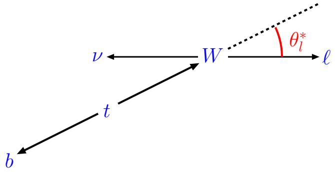
W rest frame observables

ℓ distribution in W rest frame

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_\ell^*} = \frac{3}{8}(1-\cos\theta_\ell^*)^2\, F_L + \frac{3}{4}\sin^2\theta_\ell^*\, F_0 + \frac{3}{8}(1+\cos\theta_\ell^*)^2\, F_R \qquad (F_i = \Gamma_i/\Gamma)$$



$$\begin{aligned}\Gamma_{R,L} \;=\; & \frac{g^2|\vec{q}\,|}{32\pi}\Bigg\{\left[|V_L|^2+|V_R|^2\right]\left(1-x_W^2+x_b^2\right)+\frac{m_t^2}{M_W^2}\left[|g_L|^2+|g_R|^2\right]\left(1-x_W^2-2x_b^2-x_W^2x_b^2+x_b^4\right)\\ & -4x_b\,\mathrm{Re}\;V_LV_R^*-4x_b\,\mathrm{Re}\;g_Lg_R^*-2\frac{m_t}{M_W}\mathrm{Re}\;\left[V_Lg_R^*+V_Rg_L^*\right]\left(1-x_W^2-x_b^2\right)\\ & +2\frac{m_t}{M_W}x_b\,\mathrm{Re}\;\left[V_Lg_L^*+V_Rg_R^*\right]\left(1+x_W^2-x_b^2\right)\Bigg\}\\ & \pm\frac{g^2}{64\pi}\frac{m_t^3}{M_W^2}\Big\{-x_W^2\left[|V_L|^2-|V_R|^2\right]+\left[|g_L|^2-|g_R|^2\right]\left(1-x_b^2\right)\\ & +2x_W\,\mathrm{Re}\;\left[V_Lg_R^*-V_Rg_L^*\right]+2x_Wx_b\,\mathrm{Re}\;\left[V_Lg_L^*-V_Rg_R^*\right]\Big\}\left(1-2x_W^2-2x_b^2+x_W^4-2x_W^2x_b^2+x_b^4\right)\end{aligned}$$

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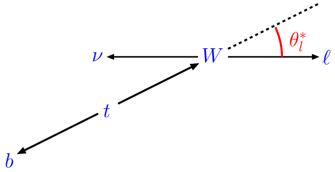
[JAAS et al EPJC ’07]

W rest frame observables

ℓ distribution in W rest frame

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_\ell^*} = \frac{3}{8}(1-\cos\theta_\ell^*)^2\, F_L + \frac{3}{4}\sin^2\theta_\ell^*\, F_0 + \frac{3}{8}(1+\cos\theta_\ell^*)^2\, F_R \qquad (F_i = \Gamma_i/\Gamma)$$



$$\begin{aligned}
\Gamma_0 \;=\; & \frac{g^2|\vec{q}\,|}{32\pi}\left\{ \frac{m_t^2}{M_W^2}\left[|V_L|^2+|V_R|^2\right]\left(1-x_W^2-2x_b^2-x_W^2x_b^2+x_b^4\right) + \left[|g_L|^2+|g_R|^2\right]\left(1-x_W^2+x_b^2\right)\right. \\
& -4x_b\,\mathrm{Re}\;V_LV_R^* - 4x_b\,\mathrm{Re}\;g_Lg_R^* - 2\frac{m_t}{M_W}\mathrm{Re}\;\left[V_Lg_R^*+V_Rg_L^*\right]\left(1-x_W^2-x_b^2\right) \\
& \left. +2\frac{m_t}{M_W}x_b\,\mathrm{Re}\;\left[V_Lg_L^*+V_Rg_R^*\right]\left(1+x_W^2-x_b^2\right)\right\}
\end{aligned}$$

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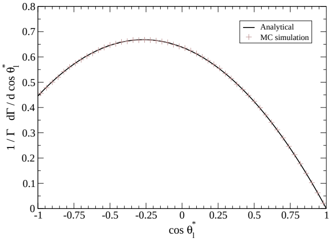
[JAAS et al EPJC ’07]

W helicity fractions and related observables



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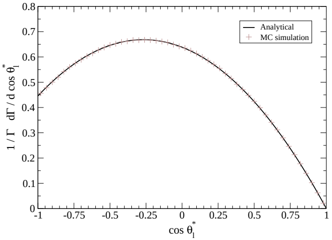
W helicity fractions and related observables

Fit ➞ F_0, F_L, F_R

$$F_0 + F_L + F_R = 1$$



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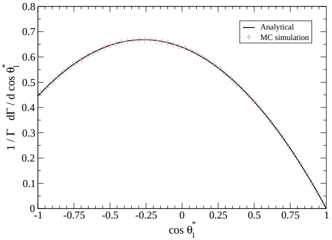
W helicity fractions and related observables



Fit → F_0, F_L, F_R

$F_0 + F_L + F_R = 1$

Fit → $\rho_R \equiv \frac{F_R}{F_0}, \rho_L \equiv \frac{F_L}{F_0}$

Independent

ρ_R ☞ Best limit on V_R, g_L

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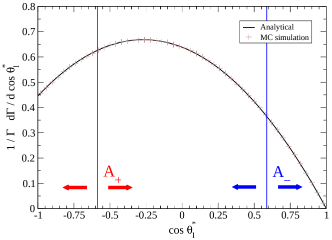
W helicity fractions and related observables



Fit → F_0, F_L, F_R

$F_0 + F_L + F_R = 1$

Fit → $\rho_R \equiv \frac{F_R}{F_0}, \rho_L \equiv \frac{F_L}{F_0}$

Independent

ρ_R ☞ Best limit on V_R, g_L

Count events → $A_\pm$

Asym. around $\mp(2^{2/3} - 1)$

A_+ ☞ Best limit on g_R

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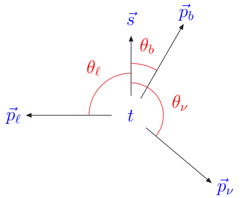
Top spin asymmetries

Polarised top decay

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_X} = \frac{1+\alpha_X\cos\theta_X}{2}$$

[Jezabek, Kuhn, PLB '94]



$$\begin{aligned}
a_{\ell^+} = &\left[V_L^2 - V_R^2\right]\left(1 + x_W^2 - 2x_b^2 - 2x_W^4 + x_W^2 x_b^2 + x_b^4\right) + 2\left[g_L^2 - g_R^2\right]\left(1 - \frac{x_W^2}{2} - 2x_b^2 - \frac{x_W^4}{2} - \frac{x_W^2 x_b^2}{2} + x_b^4\right)\\
&- 12x_W^2 x_b\, V_L V_R - 12x_W^2 x_b\, g_L g_R - 6x_W\left[V_L g_R + V_R g_L\right]\left(1 - x_W^2 - x_b^2\right) + 6x_W x_b\left[V_L g_L - V_R g_R\right]\left(1 + x_W^2 - x_b^2\right)\\
&+ 12x_W^2(V_R^2 - g_R^2) + \frac{m_t}{|\vec{q}|}\log\frac{E_W + |\vec{q}|}{E_W - |\vec{q}|}\left[-6x_W^4 V_R^2 + 6x_W^2 g_R^2(1 - x_b^2) + 12x_W^3 x_b V_R g_R\right]
\end{aligned}$$

$$\begin{aligned}
a_0 = &\left[V_L^2 + V_R^2\right]\left(1 + x_W^2 - 2x_b^2 - 2x_W^4 + x_W^2 x_b^2 + x_b^4\right) + 2\left[g_L^2 + g_R^2\right]\left(1 - \frac{x_W^2}{2} - 2x_b^2 - \frac{x_W^4}{2} - \frac{x_W^2 x_b^2}{2} + x_b^4\right)\\
&- 12x_W^2 x_b\, V_L V_R - 12x_W^2 x_b\, g_L g_R - 6x_W\left[V_L g_R + V_R g_L\right]\left(1 - x_W^2 - x_b^2\right) + 6x_W x_b\left[V_L g_L + V_R g_R\right]\left(1 + x_W^2 - x_b^2\right)
\end{aligned}$$

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[JAAS et al. EPJC '07]

Top spin asymmetries

Top pair production: spin correlation asymmetries

X = top decay product ➞ $\vec{p}_X$ = momentum in t rest frame

$\bar{X}'$ = antitop decay product ➞ $\vec{p}_{\bar{X}'}$ = momentum in $\bar{t}$ rest frame

$\vec{p}_t$ = t momentum in CM frame $\vec{p}_{\bar{t}}$ = $\bar{t}$ momentum in CM frame

$Q = \cos(\vec{p}_X, \vec{p}_t)\,\cos(\vec{p}_{\bar{X}'}, \vec{p}_{\bar{t}})$ ➞

$$A_{X\bar{X}'} \equiv \frac{N(Q>0)-N(Q<0)}{N(Q>0)+N(Q<0)} = \frac{1}{4}\,C\,\alpha_X\,\alpha_{\bar{X}'} \quad [C = 0.319]$$

$Q = \cos(\vec{p}_X, \vec{p}_{\bar{X}'})$ ➞

$$\tilde{A}_{X\bar{X}'} \equiv \frac{N(Q>0)-N(Q<0)}{N(Q>0)+N(Q<0)} = \frac{1}{2}\,D\,\alpha_X\,\alpha_{\bar{X}'} \quad [D = -0.217]$$

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[Bernreuther et al. NPB '04]

Top spin asymmetries

tj production: spin asymmetries

X = top decay product → $\vec{p}_X$ = momentum in t rest frame

$\vec{p}_j$ = jet momentum in t rest frame

$Q = \cos(\vec{p}_X, \vec{p}_j)$ →

$$A_X \equiv \frac{N(Q>0) - N(Q<0)}{N(Q>0) + N(Q<0)} = \frac{1}{2} P \alpha_X \quad [P = 0.95\ (t) \quad P = -0.93\ (\bar{t})]$$

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[Mahlon, Parke, PLB '00]

Ratios of top spin asymmetries

Ratios of asymmetries depend only on α

$$t\bar{t} \text{ production} \quad \rightarrow \quad \frac{A_{bj}}{A_{\ell j}} = \frac{\tilde{A}_{bj}}{\tilde{A}_{\ell j}} = \frac{\alpha_b}{\alpha_\ell} \equiv r_{b\ell}$$

$$tj/\bar{t}\bar{b}j \text{ production} \quad \rightarrow \quad \frac{A_b}{A_\ell} = \frac{\alpha_b}{\alpha_\ell} = r_{b\ell}$$

Guessed precision

$$r_{bl} = -0.406 \pm 0.008$$

SM central value, relative error 2%