Effective operators in top physics

J. A. Aguilar-Saavedra

Departamento de Física Teórica y del Cosmos
Universidad de Granada

ICHEP, Paris 23/07/2010

Based on

- JAAS, J. Carvalho, N. Castro, A. Onofre, F. Veloso, *"Probing anomalous Wtb couplings in top pair decays"*, EPJC '07
- JAAS, J. Carvalho, N. Castro, A. Onofre, F. Veloso, *"ATLAS sensitivity to Wtb anomalous couplings in top quark decays"*, EPJC '08
- JAAS, *"Single top quark production at LHC with anomalous Wtb couplings"*, NPB '08
- JAAS, *"A minimal set of top anomalous couplings"*, NPB '09
- JAAS, *"A minimal set of top-Higgs anomalous couplings"*, NPB '09
- JAAS, J. Bernabéu, *"W polarisation beyond helicity fractions in top quark decays"*, hep-ph '10

Probing new physics with the top quark

Preferred framework: gauge-invariant effective operators

$$\mathcal{L} = \mathcal{L}_4 + \mathcal{L}_6 + \dots$$

where

$\mathcal{L}_4 = \mathcal{L}_{\text{SM}}$ ➙ SM Lagrangian

$\mathcal{L}_6 = \sum_x \frac{\alpha_x}{\Lambda^2} O_x$ ➙ O_x gauge-invariant building blocks

Parameterise effects of new physics at scale $\Lambda > v$

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 involving 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 involving top trilinear interactions

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

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

redundants dropped

[Rattazzi, PhD Thesis]
[Grzadkowski et al NPB '04]

Operators involving top trilinear interactions

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

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

redundants dropped

[JAAS NPB ’09]

Operators involving top trilinear interactions

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

$$O_{\phi q}^{(1,i+j)} = 1/2\,[O_{\phi q}^{(1,ij)} + (O_{\phi q}^{(1,ji)})^\dagger] \quad i \leq j$$

$$O_{\phi \phi}^{ij} = i(\tilde{\phi}^\dagger D_\mu \phi)(\bar{u}_{Ri}\gamma^\mu d_{Rj})$$

$$O_{\phi u}^{i+j} = 1/2\,[O_{\phi u}^{ij} + (O_{\phi u}^{ji})^\dagger] \quad i \leq j$$

$$O_{uW}^{ij} = (\bar{q}_{Li}\sigma^{\mu\nu}\tau^I u_{Rj})\tilde{\phi}\, W_{\mu\nu}^I$$

$$O_{dW}^{ij} = (\bar{q}_{Li}\sigma^{\mu\nu}\tau^I d_{Rj})\phi\, W_{\mu\nu}^I$$

$$O_{uB\phi}^{ij} = (\bar{q}_{Li}\sigma^{\mu\nu} u_{Rj})\tilde{\phi}\, B_{\mu\nu}$$

$$O_{uG\phi}^{ij} = (\bar{q}_{Li}\lambda^a\sigma^{\mu\nu} u_{Rj})\tilde{\phi}\, G_{\mu\nu}^a$$

$$O_{u\phi}^{ij} = (\phi^\dagger\phi)(\bar{q}_{Li}u_{Rj}\tilde{\phi})$$

$$O_{Du}^{ij} = (\bar{q}_{Li}\, D_\mu u_{Rj})\, D^\mu\, \tilde{\phi}$$

$$O_{\bar{D}u}^{ij} = (D_\mu \bar{q}_{Li}\, u_{Rj})\, D^\mu\, \tilde{\phi}$$

$$O_{Dd}^{ij} = (\bar{q}_{Li}\, D_\mu d_{Rj})\, D^\mu\, \phi$$

$$O_{\bar{D}d}^{ij} = (D_\mu \bar{q}_{Li}\, d_{Rj})\, D^\mu\, \phi$$

$$O_{qW}^{ij} = \bar{q}_{Li}\gamma^\mu\tau^I D^\nu q_{Lj} W_{\mu\nu}^I$$

$$O_{qB}^{ij} = \bar{q}_{Li}\gamma^\mu D^\nu q_{Lj} B_{\mu\nu}$$

$$O_{uB}^{ij} = \bar{u}_{Ri}\gamma^\mu D^\nu u_{Rj} B_{\mu\nu}$$

$$O_{qG}^{ij} = \bar{q}_{Li}\lambda^a\gamma^\mu D^\nu q_{Lj} G_{\mu\nu}^a$$

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

redundant combinations $O_{\phi q}^{ij} - (O_{\phi q}^{ji})^\dagger$ and $O_{\phi u}^{ij} - (O_{\phi u}^{ji})^\dagger$ dropped

[JAAS NPB '09]

Technical details for fans

$$O_{qW}^{ij}, \quad O_{qB}^{ij}, \quad O_{uB}^{ij}, \quad O_{qG}^{ij}, \quad O_{uG}^{ij}$$

int. by parts & gauge field EOM

$$O_x^{ij} = \frac{1}{2}\left[O_x^{ij} + (O_x^{ji})^\dagger\right] + \frac{1}{2}\left[O_x^{ij} - (O_x^{ji})^\dagger\right]$$

$$\begin{aligned} O_{qW}^{ij} + (O_{qW}^{ji})^\dagger &= \frac{g}{4}\left[O_{\phi q}^{(3,ij)} + (O_{\phi q}^{(3,ji)})^\dagger\right] + \frac{g}{4}\, O_{lq}^{(3,kkij)} + \frac{g}{3}\, O_{qq}^{(1,1,ikkj)} \\ &\quad + \frac{g}{2}\, O_{qq}^{(8,1,ikkj)} - \frac{g}{2}\, O_{qq}^{(1,1,ijkk)} \\ O_{qB}^{ij} + (O_{qB}^{ji})^\dagger &= \frac{g}{4}\left[O_{\phi q}^{(1,ij)} + (O_{\phi q}^{(1,ji)})^\dagger\right] - \frac{g'}{4}\, O_{lq}^{(1,kkij)} + g'\, O_{qe}^{ikkj} + \frac{g'}{6}\, O_{qq}^{(1,1,ijkk)} \\ &\quad - \frac{2g'}{9}\, O_{qu}^{(1,ikkj)} - \frac{g'}{3}\, O_{qu}^{(8,ikkj)} + \frac{g'}{9}\, O_{qd}^{(1,ikkj)} - \frac{g'}{6}\, O_{qd}^{(8,ikkj)} \end{aligned}$$

Technical details for fans

$$O_{qW}^{ij}, \quad O_{qB}^{ij}, \quad O_{uB}^{ij}, \quad O_{qG}^{ij}, \quad O_{uG}^{ij}$$

int. by parts & gauge field EOM

$$O_x^{ij} = \frac{1}{2}\left[O_x^{ij} + (O_x^{ji})^\dagger\right] + \frac{1}{2}\left[O_x^{ij} - (O_x^{ji})^\dagger\right]$$

$$\begin{aligned} O_{uB}^{ij} + (O_{uB}^{ji})^\dagger \quad = \quad & \frac{g}{4}\left[O_{\phi u}^{ij} + (O_{\phi u}^{ji})^\dagger\right] + \frac{g'}{2} O_{lu}^{kjik} - \frac{g'}{2} O_{eu}^{kkij} - \frac{g'}{18} O_{qu}^{(1,kjik)} \\ & - \frac{g'}{12} O_{qu}^{(8,kjik)} + \frac{2g'}{3} O_{uu}^{(1,ijkk)} - \frac{g'}{6} O_{ud}^{(1,ijkk)} \end{aligned}$$

Technical details for fans

$$O_{qW}^{ij}, \quad O_{qB}^{ij}, \quad O_{uB}^{ij}, \quad O_{qG}^{ij}, \quad O_{uG}^{ij}$$

int. by parts & gauge field EOM

$$O_x^{ij} = \frac{1}{2}\left[O_x^{ij} + (O_x^{ji})^\dagger\right] + \frac{1}{2}\left[O_x^{ij} - (O_x^{ji})^\dagger\right]$$

$$O_{qG}^{ij} + (O_{qG}^{ji})^\dagger = \frac{g_s}{2} O_{qq}^{(8,1,ijkk)} - \frac{8g_s}{9} O_{qu}^{(1,ikkj)} + \frac{g_s}{6} O_{qu}^{(8,ikkj)} - \frac{8g_s}{9} O_{qd}^{(1,ikkj)} + \frac{g_s}{6} O_{qd}^{(8,ikkj)}$$

$$O_{uG}^{ij} + (O_{uG}^{ji})^\dagger = -\frac{8g_s}{9} O_{qu}^{(1,kjik)} + \frac{g_s}{6} O_{qu}^{(8,kjik)} + g_s O_{uu}^{(1,ikkj)} - \frac{g_s}{3} O_{uu}^{(1,ijkk)} + \frac{g_s}{4} O_{ud}^{(8,ijkk)}$$

Technical details for fans

$$O^{ij}_{qW}, \quad O^{ij}_{qB}, \quad O^{ij}_{uB}, \quad O^{ij}_{qG}, \quad O^{ij}_{uG}$$

dual fields & quark EOM & Bianchi

$$O^{ij}_x = \frac{1}{2}\left[O^{ij}_x + (O^{ji}_x)^\dagger\right] + \frac{1}{2}\left[O^{ij}_x - (O^{ji}_x)^\dagger\right]$$

$$\begin{aligned}
O^{ij}_{qW} - (O^{ji}_{qW})^\dagger &= -\frac{1}{4}\left[Y^u_{jk}\, O^{ik}_{uW} + Y^d_{jk}\, O^{ik}_{dW} - Y^{u\dagger}_{ki}\, (O^{jk}_{uW})^\dagger - Y^{d\dagger}_{ki}\, (O^{jk}_{dW})^\dagger\right] \\
O^{ij}_{qB} - (O^{ji}_{qB})^\dagger &= -\frac{1}{4}\left[Y^u_{jk}\, O^{ik}_{uB\phi} + Y^d_{jk}\, O^{ik}_{dB\phi} - Y^{u\dagger}_{ki}\, (O^{jk}_{uB\phi})^\dagger - Y^{d\dagger}_{ki}\, (O^{jk}_{dB\phi})^\dagger\right] \\
O^{ij}_{uB} - (O^{ji}_{uB})^\dagger &= \frac{1}{4}\left[Y^u_{ki}\, O^{kj}_{uB\phi} - Y^{u\dagger}_{jk}\, (O^{ki}_{uB\phi})^\dagger\right]
\end{aligned}$$

Technical details for fans

$$O_{qW}^{ij}, \quad O_{qB}^{ij}, \quad O_{uB}^{ij}, \quad O_{qG}^{ij}, \quad O_{uG}^{ij}$$

dual fields & quark EOM & Bianchi

$$O_x^{ij} = \frac{1}{2}\left[O_x^{ij} + (O_x^{ji})^\dagger\right] + \frac{1}{2}\left[O_x^{ij} - (O_x^{ji})^\dagger\right]$$

$$O_{qG}^{ij} - (O_{qG}^{ji})^\dagger = -\frac{1}{4}\left[Y_{jk}^u\, O_{uG\phi}^{ik} + Y_{jk}^d\, O_{dG\phi}^{ik} - Y_{ki}^{u\dagger}\,(O_{uG\phi}^{jk})^\dagger - Y_{ki}^{d\dagger}\,(O_{dG\phi}^{jk})^\dagger\right]$$

$$O_{uG}^{ij} - (O_{uG}^{ji})^\dagger = \frac{1}{4}\left[Y_{ki}^u\, O_{uG\phi}^{kj} - Y_{jk}^{u\dagger}\,(O_{uG\phi}^{ki})^\dagger\right]$$

Technical details for fans

$O^{ij}_{Du}, \quad O^{ij}_{\bar{D}u}, \quad O^{ij}_{Dd}, \quad O^{ij}_{\bar{D}d}$

int. by parts & scalar EOM

$$O^{ij}_{Dx,\bar{D}x} = \frac{1}{2}\left[O^{ij}_{Dx} + O^{ij}_{\bar{D}x}\right] \pm \frac{1}{2}\left[O^{ij}_{Dx} - O^{ij}_{\bar{D}x}\right]$$

$$\begin{aligned} O^{ij}_{Du} + O^{ij}_{\bar{D}u} &= -m^2 \bar{q}_{Li} u_{Rj} \tilde{\phi} + \lambda O^{ij}_{u\phi} + Y^e_{kl} O^{ijkl}_{lq} + Y^{u\dagger}_{kl} O^{(1,ijkl)}_{qu} + Y^d_{kl} O^{(1,ijkl)}_{qq} \\ O^{ij}_{Dd} + O^{ij}_{\bar{D}d} &= -m^2 \bar{q}_{Li} d_{Rj} \phi + \lambda O^{ij}_{d\phi} + Y^{e\dagger}_{kl} (O^{lkji}_{qde})^\dagger + Y^u_{kl} O^{(1,klij)}_{qq} + Y^{d\dagger}_{kl} O^{(1,ijkl)}_{qd} \end{aligned}$$

Technical details for fans

$$O^{ij}_{Du}, \quad O^{ij}_{\bar{D}u}, \quad O^{ij}_{Dd}, \quad O^{ij}_{\bar{D}d}$$

int. by parts & algebra

$$O^{ij}_{Dx,\bar{D}x} = \frac{1}{2}\left[O^{ij}_{Dx} + O^{ij}_{\bar{D}x}\right] \pm \frac{1}{2}\left[O^{ij}_{Dx} - O^{ij}_{\bar{D}x}\right]$$

$$\begin{aligned} O^{ij}_{Du} - O^{ij}_{\bar{D}u} &= -\frac{g}{4} O^{ij}_{uW} + \frac{g'}{4} O^{ij}_{uB\phi} - \frac{1}{2} Y^{u\dagger}_{jk} \left[(O^{(3,ki)}_{\phi q})^\dagger - (O^{(1,ki)}_{\phi q})^\dagger \right] \\ &\quad + Y^{u\dagger}_{ki} (O^{jk}_{\phi u})^\dagger - Y^{d\dagger}_{ki} (O^{jk}_{\phi\phi})^\dagger \\ O^{ij}_{Dd} - O^{ij}_{\bar{D}d} &= -\frac{g}{4} O^{ij}_{dW} - \frac{g'}{4} O_{dB\phi} - \frac{1}{2} Y^{d\dagger}_{jk} \left[O^{(3,ik)}_{\phi q} + O^{(1,ik)}_{\phi q} \right] \\ &\quad - Y^{u\dagger}_{ki} O^{kj}_{\phi\phi} - Y^{d\dagger}_{ki} O^{kj}_{\phi d} \end{aligned}$$

Technical details for fans

$$O_{\phi q}^{(3,ij)}, \quad O_{\phi q}^{(1,ij)}, \quad O_{\phi u}^{ij}$$

int. by parts & quark EOM

$$\begin{aligned}
O_{\phi q}^{(3,ij)} - (O_{\phi q}^{(3,ji)})^\dagger &= Y_{jk}^u O_{u\phi}^{ik} - Y_{jk}^d O_{d\phi}^{ik} - Y_{ki}^{u\dagger} (O_{u\phi}^{jk})^\dagger + Y_{ki}^{d\dagger} (O_{d\phi}^{jk})^\dagger \\
O_{\phi q}^{(1,ij)} - (O_{\phi q}^{(1,ji)})^\dagger &= -Y_{jk}^u O_{u\phi}^{ik} - Y_{jk}^d O_{d\phi}^{ik} + Y_{ki}^{u\dagger} (O_{u\phi}^{jk})^\dagger + Y_{ki}^{d\dagger} (O_{d\phi}^{jk})^\dagger \\
O_{\phi u}^{(ij)} - (O_{\phi u}^{(ji)})^\dagger &= Y_{ki}^u O_{u\phi}^{kj} - Y_{jk}^{u\dagger} (O_{u\phi}^{ki})^\dagger
\end{aligned}$$

Technical details for fans

$$O_{\phi q}^{(3,ij)}, \quad O_{\phi q}^{(1,ij)}, \quad O_{\phi u}^{ij}$$

Not all i,j flavour combinations independent!

	Instead of	O_x^{ij}	$i,j = 1,2,3$
→	use	$O_x^{i+j} = \frac{1}{2}\left[O_x^{ij} + (O_x^{ji})^\dagger\right]$	$i \leq j = 1,2,3$
	and drop	$O_x^{i-j} = \frac{1}{2}\left[O_x^{ij} - (O_x^{ji})^\dagger\right]$	$i \leq j = 1,2,3$

Technical details for fans

$$O_{\phi q}^{(3,ij)}, \quad O_{\phi q}^{(1,ij)}, \quad O_{\phi u}^{ij}$$

Independent operators:

$$O_{\phi q}^{(3,i+j)} = \frac{i}{2} \left[\phi^\dagger (\tau^I D_\mu - \overleftarrow{D}_\mu \tau^I) \phi \right] (\bar{q}_{Li} \gamma^\mu \tau^I q_{Lj})$$

$$O_{\phi q}^{(1,i+j)} = \frac{i}{2} (\phi^\dagger \overleftrightarrow{D^\mu} \phi)(\bar{q}_{Li} \gamma^\mu q_{Lj})$$

$$O_{\phi u}^{i+j} = \frac{i}{2} (\phi^\dagger \overleftrightarrow{D^\mu} \phi)(\bar{u}_{Ri} \gamma^\mu u_{Rj})$$

This is not a change of basis: operators in blue included in BW list

$$O_{dB\phi}^{ij} = (\bar{q}_{Li}\sigma^{\mu\nu} d_{Rj})\phi B_{\mu\nu}$$

$$O_{dG\phi}^{ij} = (\bar{q}_{Li}\lambda^a \sigma^{\mu\nu} d_{Rj})\phi G_{\mu\nu}^a$$

$$O_{\phi d}^{ij} = i(\phi^\dagger D_\mu \phi)(\bar{d}_{Ri}\gamma^\mu d_{Rj})$$

$$O_{d\phi}^{ij} = (\phi^\dagger \phi)\bar{q}_{Li} d_{Rj}\phi$$

$$O_{qq}^{(1,1,ijkl)} = 1/2\,(\bar{q}_{Li}\gamma^\mu q_{Lj})(\bar{q}_{Lk}\gamma_\mu q_{Ll})$$

$$O_{qq}^{(8,1,ijkl)} = 1/2\,(\bar{q}_{Li}\gamma^\mu \lambda^a q_{Lj})(\bar{q}_{Lk}\gamma_\mu \lambda^a q_{Ll})$$

$$O_{lq}^{(1,ijkl)} = (\bar{l}_{Li}\gamma^\mu l_{Lj})(\bar{q}_{Lk}\gamma_\mu q_{Ll})$$

$$O_{lq}^{(3,ijkl)} = (\bar{l}_{Li}\gamma^\mu \tau^I l_{Lj})(\bar{q}_{Lk}\gamma_\mu \tau^I q_{Ll})$$

$$O_{uu}^{(1,ijkl)} = 1/2\,(\bar{u}_{Ri}\gamma^\mu u_{Rj})(\bar{u}_{Rk}\gamma_\mu u_{Rl})$$

$$O_{eu}^{ijkl} = (\bar{e}_{Ri}\gamma^\mu e_{Rj})(\bar{u}_{Rk}\gamma_\mu u_{Rl})$$

$$O_{ud}^{(1,ijkl)} = (\bar{u}_{Ri}\gamma^\mu u_{Rj})(\bar{d}_{Rk}\gamma_\mu d_{Rl})$$

$$O_{ud}^{(8,ijkl)} = (\bar{u}_{Ri}\gamma^\mu \lambda^a u_{Rj})(\bar{d}_{Rk}\gamma_\mu \lambda^a d_{Rl})$$

$$O_{lu}^{ijkl} = (\bar{l}_{Li} u_{Rj})(\bar{u}_{Rk} l_{Ll})$$

$$O_{qe}^{ijkl} = (\bar{q}_{Li} e_{Rj})(\bar{e}_{Rk} q_{Ll})$$

$$O_{qu}^{(1,ijkl)} = (\bar{q}_{Li} u_{Rj})(\bar{u}_{Rk} q_{Ll})$$

$$O_{qu}^{(8,ijkl)} = (\bar{q}_{Li}\lambda^a u_{Rj})(\bar{u}_{Rk}\lambda^a q_{Ll})$$

$$O_{qd}^{(1,ijkl)} = (\bar{q}_{Li} d_{Rj})(\bar{d}_{Rk} q_{Ll})$$

$$O_{qd}^{(8,ijkl)} = (\bar{q}_{Li}\lambda^a d_{Rj})(\bar{d}_{Rk}\lambda^a q_{Ll})$$

$$O_{qde}^{ijkl} = (\bar{l}_{Li} e_{Rj})(\bar{d}_{Rk} q_{Ll})$$

$$O_{qq}^{(1,ijkl)} = (\bar{q}_{Li} u_{Rj})\left[(\bar{q}_{Lk}\epsilon)^T d_{Rl}\right]$$

$$O_{lq}^{ijkl} = (\bar{q}_{Li} u_{Rj})\left[(\bar{l}_{Lk}\epsilon)^T e_{Rl}\right]$$

A minimal set of top anomalous couplings

Wtb vertex - before

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

A minimal set of top anomalous couplings

Wtb vertex - without redundant operators

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

A minimal set of top anomalous couplings

dim 6 operator contributions to Wtb vertex

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

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

Top couplings in a nutshell:

1. Gauge interactions: only γ^μ and $\sigma^{\mu\nu} q_\nu$ terms
2. Higgs: only scalar and pseudo-scalar terms

☞ This is general for any fermion and process, not only the top quark!

This simplifies [phenomenological analyses / Monte Carlo building]

The leading order approximation

Example: Wtb vertex from dim 6 operators

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

$$q = p_t - p_b = p_W$$

Anomalous couplings $\sim \frac{v^2}{\Lambda^2}$ ➜ an expansion seems reasonable

… but which one?

$$\left. \begin{array}{r} \text{SM} \times \text{dim } 6 \sim 1/\Lambda^2 \\ (\text{dim } 6)^2 \sim 1/\Lambda^4 \end{array} \right\}$$

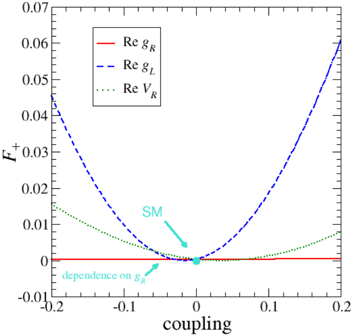
➜ some authors only consider "leading" $1/\Lambda^2$ effects, $m_b = 0$

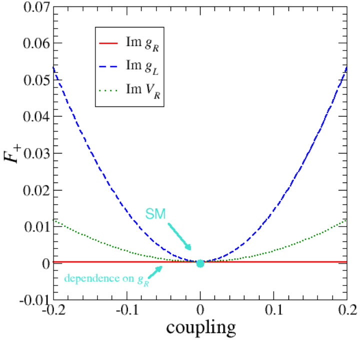
The $1/\Lambda^2$ approximation

	$1/\Lambda^2$	$1/\Lambda^4$
$\bar{b}_L \gamma^\mu t_L$	$\delta V_L = C_{\phi q}^{(3,3+3)*} \frac{v^2}{\Lambda^2}$	$(\delta V_L)^2 + \text{dim 8 } \bar{L}L$
$\bar{b}_R \gamma^\mu t_R$	✘	$(\delta V_R)^2 = \frac{1}{4} (C_{\phi\phi}^{33*})^2 \frac{v^4}{\Lambda^4}$
$\bar{b}_R \sigma^{\mu\nu} t_L$	✘	$(\delta g_L)^2 = 2 (C_{dW}^{33*})^2 \frac{v^4}{\Lambda^4}$
$\bar{b}_L \sigma^{\mu\nu} t_R$	$\delta g_R = \sqrt{2} C_{uW}^{33} \frac{v^2}{\Lambda^2}$	$(\delta g_R)^2 + \text{dim 8 } \bar{L}R$

keep only $1/\Lambda^2$ ☞ is it sensible?

Example: W helicity fraction F_+ , $F_+ \sim 0$ in the SM





to order $1/\Lambda^2$ ➡ $F_+ = F_+^{\rm SM}$

approximation not sensible to explore NP effects

In the $1/\Lambda^2$ approximation, many observables do not receive contributions from new physics

Another example: FCNC

FCNC absent in the SM ☞ BSM it is order $1/\Lambda^4$

Then, one must go beyond the $1/\Lambda^2$ approximation to have BSM phenomenology

In the $1/\Lambda^2$ approximation, many observables do not receive contributions from new physics

Another example: FCNC

FCNC absent in the SM ☞ BSM it is order $1/\Lambda^4$

Then, one must go beyond the $1/\Lambda^2$ approximation to have BSM phenomenology

In the $1/\Lambda^2$ approximation, many observables do not receive contributions from new physics

Another example: FCNC

FCNC absent in the SM ☞ BSM it is order $1/\Lambda^4$

Then, one must go beyond the $1/\Lambda^2$ approximation to have BSM phenomenology

It makes sense to consider the lowest non-zero order for each type of contribution

☞ the leading order approximation

- ★ justified by phenomenology ➙ different NP structures give different effects
- ★ consistent within a $1/\Lambda$ expansion

The leading order approximation

	$1/\Lambda^2$	$1/\Lambda^4$
$\bar b_L \gamma^\mu t_L$	$\delta V_L = C_{\phi q}^{(3,3+3)*} \frac{v^2}{\Lambda^2}$	$(\delta V_L)^2 + \text{dim 8 } \bar L L$
$\bar b_R \gamma^\mu t_R$	✗	$(\delta V_R)^2 = \frac{1}{4} (C_{\phi\phi}^{33*})^2 \frac{v^4}{\Lambda^4}$
$\bar b_R \sigma^{\mu\nu} t_L$	✗	$(\delta g_L)^2 = 2 (C_{dW}^{33*})^2 \frac{v^4}{\Lambda^4}$
$\bar b_L \sigma^{\mu\nu} t_R$	$\delta g_R = \sqrt{2} C_{uW}^{33} \frac{v^2}{\Lambda^2}$	$(\delta g_R)^2 + \text{dim 8 } \bar L R$

… and with $m_b \neq 0$, $V_R \frac{m_b}{m_t} \sim V_R^2$, $g_L \frac{m_b}{m_t} \sim g_L^2$ of the same order

The leading order approximation

	$1/\Lambda^2$	$1/\Lambda^4$
$\bar{b}_L \gamma^\mu t_L$	$\delta V_L = C_{\phi q}^{(3,3+3)*} \frac{v^2}{\Lambda^2}$	$(\delta V_L)^2 + \text{dim } 8\ \bar{L}L$
$\bar{b}_R \gamma^\mu t_R$	✘	$(\delta V_R)^2 = \frac{1}{4} (C_{\phi\phi}^{33*})^2 \frac{v^4}{\Lambda^4}$
$\bar{b}_R \sigma^{\mu\nu} t_L$	✘	$(\delta g_L)^2 = 2 (C_{dW}^{33*})^2 \frac{v^4}{\Lambda^4}$
$\bar{b}_L \sigma^{\mu\nu} t_R$	$\delta g_R = \sqrt{2} C_{uW}^{33} \frac{v^2}{\Lambda^2}$	$(\delta g_R)^2 + \text{dim } 8\ \bar{L}R$

… and with $m_b \neq 0$, $V_R \frac{m_b}{m_t} \sim V_R^2$, $g_L \frac{m_b}{m_t} \sim g_L^2$ of the same order

Application: *W* polarisation beyond helicity fractions

$$\left.\begin{array}{l}\Gamma_+\\ \Gamma_0\\ \Gamma_-\end{array}\right\} \text{partial widths for } t \to Wb \text{ with } W \text{ helicity} \left\{\begin{array}{r}+1\\ 0\\ -1\end{array}\right.$$

helicity fractions $F_i = \Gamma_i / \Gamma$ where $\Gamma = \Gamma_+ + \Gamma_0 + \Gamma_-$

In the SM at tree level

$$F_+ = 3.6 \times 10^{-4}$$
$$F_0 = 0.702$$
$$F_- = 0.297$$

Measured in $t\bar{t}$ production

$$F_0 = 0.88 \pm 0.125$$
$$F_+ = -0.15 \pm 0.0921$$

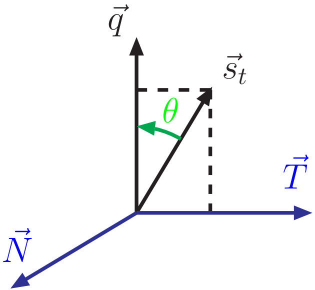
[CDF ’10]

They give information about the *Wtb* interaction

[Kane, Ladinsky, Yuan PRD ’92]

A new idea

Use other directions to probe W spin



Transverse and normal directions

$\vec{q}$ → W mom in t rest frame

$\vec{s}_t$ → top spin

$$\vec{N} = \vec{s}_t \times \vec{q}$$

$$\vec{T} = \vec{q} \times \vec{N}$$

meaningful for polarised t decays

(e.g. in single top production)

In general, density matrix $$\left(\Gamma_{ij} = \frac{g^2 |\vec{q}\,|}{128\pi^2} \int M_{ij} \; d\cos\theta \, d\phi \right)$$

$$M_{00} = A_0 + 2\frac{|\vec{q}\,|}{m_t} A_1 \cos\theta$$

$$M_{\pm\pm} = B_0 \,(1 \pm \cos\theta) \pm 2\frac{|\vec{q}\,|}{m_t} B_1 \,(1 \pm \cos\theta)$$

$$M_{0\pm} = M^*_{\pm 0} = \left[\frac{m_t}{\sqrt{2} M_W} (C_0 - i\, D_0) \pm \frac{|\vec{q}\,|}{\sqrt{2} M_W} (C_1 - i\, D_1) \right] \sin\theta e^{\pm i\phi}$$

$$M_{+-} = M_{-+} = 0$$

helicity fractions $$\left\{ \begin{array}{l} F_0 = \Gamma_{00}/\Gamma \\ F_+ = \Gamma_{++}/\Gamma \\ F_- = \Gamma_{--}/\Gamma \end{array} \right\}$$ test A_0, B_0, B_1

transverse / normal polarisation involve off-diagonal C_0 / D_1

Form factors including b mass $(x_b = m_b/mt, x_W = M_W/m_t)$

$$A_0 = \frac{m_t^2}{M_W^2}\left[|V_L|^2 + |V_R|^2\right]\left(1 - x_W^2\right) + \left[|g_L|^2 + |g_R|^2\right]\left(1 - x_W^2\right) - 4x_b \,\mathrm{Re}\,\left[V_L V_R^* + g_L g_R^*\right]$$
$$- 2\frac{m_t}{M_W}\mathrm{Re}\,\left[V_L g_R^* + V_R g_L^*\right]\left(1 - x_W^2\right) + 2\frac{m_t}{M_W}x_b\,\mathrm{Re}\,\left[V_L g_L^* + V_R g_R^*\right]\left(1 + x_W^2\right)$$

$$A_1 = \frac{m_t^2}{M_W^2}\left[|V_L|^2 - |V_R|^2\right] - \left[|g_L|^2 - |g_R|^2\right] - 2\frac{m_t}{M_W}\mathrm{Re}\,\left[V_L g_R^* - V_R g_L^*\right] + 2\frac{m_t}{M_W}x_b\mathrm{Re}\,\left[V_L g_L^* - V_R g_R^*\right]$$

$$B_0 = \left[|V_L|^2 + |V_R|^2\right]\left(1 - x_W^2\right) + \frac{m_t^2}{M_W^2}\left[|g_L|^2 + |g_R|^2\right]\left(1 - x_W^2\right) - 4x_b\,\mathrm{Re}\,\left[V_L V_R^* + g_L g_R^*\right]$$
$$- 2\frac{m_t}{M_W}\mathrm{Re}\,\left[V_L g_R^* + V_R g_L^*\right]\left(1 - x_W^2\right) + 2\frac{m_t}{M_W}x_b\,\mathrm{Re}\,\left[V_L g_L^* + V_R g_R^*\right]\left(1 + x_W^2\right)$$

$$B_1 = -\left[|V_L|^2 - |V_R|^2\right] + \frac{m_t^2}{M_W^2}\left[|g_L|^2 - |g_R|^2\right] + 2\frac{m_t}{M_W}\,\mathrm{Re}\,\left[V_L g_R^* - V_R g_L^*\right] + 2\frac{m_t}{M_W}x_b\,\mathrm{Re}\,\left[V_L g_L^* - V_R g_R^*\right]$$

$$C_0 = \left[|V_L|^2 + |V_R|^2 + |g_L|^2 + |g_R|^2\right]\left(1 - x_W^2\right) - 2x_b\,\mathrm{Re}\,\left[V_L V_R^* + g_L g_R^*\right]\left(1 + x_W^2\right)$$
$$- \frac{m_t}{M_W}\mathrm{Re}\,\left[V_L g_R^* + V_R g_L^*\right]\left(1 - x_W^4\right) + 4x_W x_b\,\mathrm{Re}\,\left[V_L g_L^* + V_R g_R^*\right]$$

$$C_1 = 2\left[-|V_L|^2 + |V_R|^2 + |g_L|^2 - |g_R|^2\right] + 2\frac{m_t}{M_W}\mathrm{Re}\,\left[V_L g_R^* - V_R g_L^*\right]\left(1 + x_W^2\right)$$

$$D_0 = \frac{m_t}{M_W}\mathrm{Im}\,\left[V_L g_R^* + V_R g_L^*\right]\left(1 - 2x_W^2 + x_W^4\right)$$

$$D_1 = -4x_b\,\mathrm{Im}\,\left[V_L V_R^* + g_L g_R^*\right] - 2\frac{m_t}{M_W}\mathrm{Im}\,\left[V_L g_R^* - V_R g_L^*\right](1 - x_W^2)$$

Highlights (I): limits on Fs

Sum rule

$$F_0^T = F_0^N = \frac{1}{2}(F_+ + F_-)$$

fixes F_0^T, F_0^N from helicity fraction measurements

☞ but the $F_\pm^T$, $F_\pm^N$ components are free!

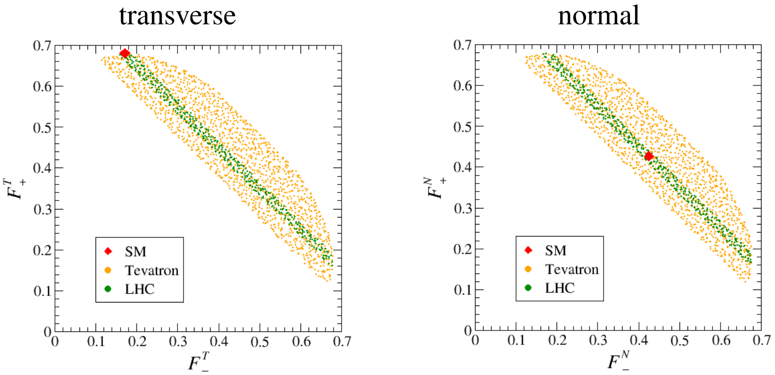
Additionally,

$$F_+^N = F_-^N = \frac{1}{2} - \frac{1}{4}(F_+ + F_-)$$

for CP-conserving Wtb vertex

Indirect limits on $F_\pm^T$, $F_\pm^N$

Limits from helicity fractions $\oplus$ single top xsec



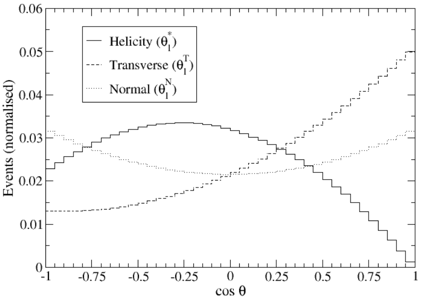
☞ ample room for departures from SM

$F_\pm^T$, $F_\pm^N$ must be measured at Tevatron and LHC

How to measure?

ℓ distributions in W rest frame $(P = 1)$

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_\ell^X} = \frac{3}{8}(1+\cos\theta_\ell^X)^2 F_+^X + \frac{3}{8}(1-\cos\theta_\ell^X)^2 F_-^X + \frac{3}{4}\sin^2\theta_\ell^X F_0^X$$



θ_ℓ^* → angle between ℓ, $\vec{q}$
determine F_+, F_0, F_-

θ_ℓ^T → angle between ℓ, $\vec{T}$
determine F_+^T, F_0^T, F_-^T

θ_ℓ^N → angle between ℓ, $\vec{N}$
determine F_+^N, F_0^N, F_-^N

How to measure?

…and when $P \neq 1$, distributions determined by "effective" Fs

$$\tilde{F}_{+}^{T,N} = \left[\frac{1+P}{2} F_{+}^{T,N} + \frac{1-P}{2} F_{-}^{T,N} \right]$$

$$\tilde{F}_{-}^{T,N} = \left[\frac{1+P}{2} F_{-}^{T,N} + \frac{1-P}{2} F_{+}^{T,N} \right]$$

$$\tilde{F}_{0}^{T,N} = F_{0}^{T,N}$$

of course, F_+, F_0, F_- determined independently of P

Highlights (II): probing CP phases

Normal polarisation

$$\Gamma_0^N = \frac{g^2|\vec{q}\,|}{32\pi} B_0 \qquad \Gamma_\pm^N = \frac{g^2|\vec{q}\,|}{32\pi}\left(\frac{A_0+B_0}{2} \pm \frac{\pi}{4}\frac{|\vec{q}\,|}{M_W} D_1\right)$$

directly probes complex phases of Wtb couplings:

$$D_1 = -4x_b \,\mathrm{Im}\,\left[V_L V_R^* + g_L g_R^*\right] - 2\frac{m_t}{M_W}\mathrm{Im}\,\left[V_L g_R^* - V_R g_L^*\right](1-x_W^2)$$

- ★ $F_+^N = F_-^N$ in the SM and for real Wtb vertex
- ★ FB asymmetry in $\cos\theta_\ell^N$ distribution $A_{\mathrm{FB}}^N = \frac{3}{4}\left[F_+^N - F_-^N\right]$ probes complex phases (is zero if Wtb vertex real, e.g. SM)

FB asymmetry A_{FB}^N

very sensitive to $\mathrm{Im}\, g_R$

$$A_{\mathrm{FB}}^N \simeq 0.64\, P\, \mathrm{Im}\, g_R \qquad (V_L = 1)$$

much more than triple-product correlations in $t\bar{t}$ production

[Gupta, Valencia PRD '09]

$$\tilde{A}_1 = (0.0886 \pm 0.0015)\, \mathrm{Im}\, g_R$$
$$\tilde{A}_2 = (0.0191 \pm 0.0015)\, \mathrm{Im}\, g_R$$
$$\tilde{A}_3 = (0.0328 \pm 0.0015)\, \mathrm{Im}\, g_R$$

equivalent to asymmetry suggested in [Kane, Ladinsky, Yuan PRD '92]
(now analytically calculated in terms of V_L, V_R, g_L, g_R)

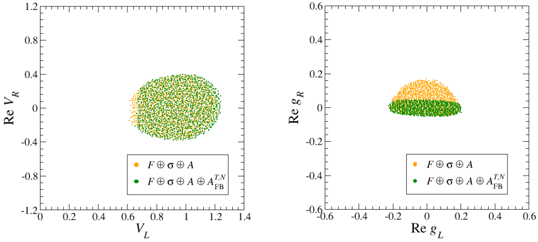
Highlights (III): The global fit

Wtb vertex (complex) can be determined in a model-independent way using:

1. helicity fractions
2. the *tW* single top cross section (no 4F contributions)
3. asymmetries in top rest frame and FB asymmetries $A_{\mathrm{FB}}^{T,N}$ in *t*-channel single top production

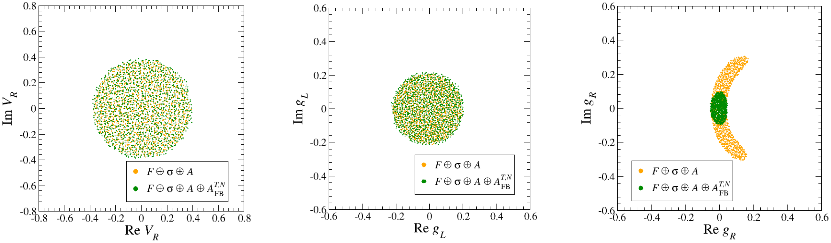
☞ single top polarisation P is taken as a free parameter and extracted from the fit

The global fit – results



$P = [0.83 - 1]$

(input $P = 0.9$)



Highlights (IV): new physics signals (at 3σ)

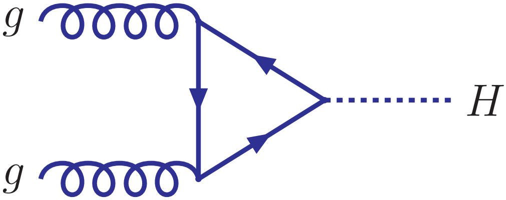
Top observables		$b \to s\gamma$
Re $V_L \leq 0.62$ Re $V_L \geq 1.21$	(σ_{tW})	Re $V_L \leq 0.83$ Re $V_L \geq 1.07$
Re $V_R \leq -0.111$ Re $V_R \geq 0.18$	(ρ_+)	Re $V_R \leq -0.0015$ Re $V_R \geq 0.0032$
$\lvert$Im $V_R\rvert \geq 0.14$	(ρ_+)	$\lvert$Im $V_R\rvert \gtrsim 0.01$
Re $g_L \leq -0.083$ Re $g_L \geq 0.051$	(ρ_+)	Re $g_L \leq -0.0019$ Re $g_L \geq 0.00090$
$\lvert$Im $g_L\rvert \geq 0.065$	(ρ_+)	$\lvert$Im $g_L\rvert \gtrsim 0.006$
$\lvert$Re $g_R\rvert \geq 0.056$	(A_+)	Re $g_R \leq -0.33$ Re $g_R \geq 0.76$
$\lvert$Im $g_R\rvert \geq 0.115$	(A_{FB}^N)	–

Additional Slides

The leading order approximation

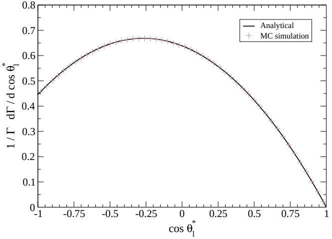
Leading order $\neq$ tree level in general

Example: $gg \to H$ at LO



- ★ it takes place at one loop
- ★ more important than other tree-level H production processes

W helicity fractions and related observables

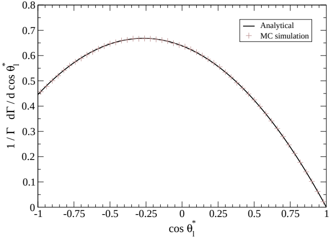


[JAAS et al. EPJC ’07,08]

W helicity fractions and related observables

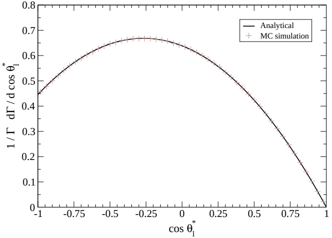
fit → F_0, F_-, F_+

(with $F_0 + F_- + F_+ = 1$)



[JAAS et al. EPJC '07,08]

W helicity fractions and related observables



[JAAS et al. EPJC '07,08]

fit ➙ F_0, F_-, F_+

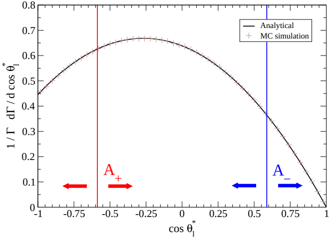
(with $F_0 + F_- + F_+ = 1$)

fit ➙ $\rho_R \equiv \frac{F_+}{F_0}, \rho_L \equiv \frac{F_-}{F_0}$

(independent parameters)

ρ_R ☞ best limit on V_R, g_L

W helicity fractions and related observables



[JAAS et al. EPJC '07,08]

fit → F_0, F_-, F_+
(with $F_0 + F_- + F_+ = 1$)

fit → $\rho_R \equiv \frac{F_+}{F_0}, \rho_L \equiv \frac{F_-}{F_0}$
(independent parameters)
ρ_R ☞ best limit on V_R, g_L

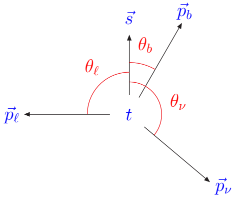
count events → $A_\pm$
asym. around $\mp(2^{2/3} - 1)$
A_+ ☞ best limit on g_R

Top rest frame observables

Polarised top decay in top rest frame

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

[Jezabek, Kuhn PLB '94]



- $\alpha_{\ell+}$, α_ν, α_b called 'spin analysing power' of ℓ^+, ν, b
- they depend on *Wtb* couplings V_L, V_R, g_L, g_R
- SM values

$\alpha_{\ell+} = 1$	$\alpha_\nu = -0.32$	$\alpha_b = -0.41$	tree level
$\alpha_{\ell+} = 0.998$	$\alpha_\nu = -0.33$	$\alpha_b = -0.39$	one loop

[Bernreuther et al. NPB '04]

- top spin not directly measurable → look for spin asymmetries

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

$Q = \cos(\vec{p}_X, \vec{p}_j)$ ➞

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

[Mahlon, Parke PLB '00]