W spin in top decays: a journey beyond helicity fractions

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Mainly based on

- JAAS, J. Bernabéu, *"W polarisation beyond helicity fractions in top quark decays"*, 1005.5382 [hep-ph today]

but also relying 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

What are 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
$$\begin{aligned} F_+ &= 3.6 \times 10^{-4} \\ F_0 &= 0.702 \\ F_- &= 0.297 \end{aligned}$$

Measured in $t\bar{t}$ production
$$\begin{aligned} F_0 &= 0.88 \pm 0.125 \\ F_+ &= -0.15 \pm 0.0921 \end{aligned}$$
[CDF '10]

They give information about the Wtb interaction

[Kane, Ladinsky, Yuan PRD '92]

The Wtb vertex

The most general Wtb vertex arising from dim 6 gauge-invariant effective operators is

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

$$q = p_t - p_b = p_W$$

Other contributing operators redundant

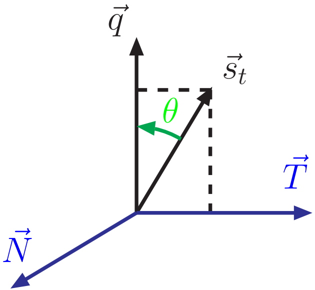
$$O_{Du}^{ij} = (\bar{q}_{Li} D_{\mu} u_{Rj}) D^{\mu} \tilde{\phi} \qquad O_{\bar{D}u}^{ij} = (D_{\mu} \bar{q}_{Li} u_{Rj}) D^{\mu} \tilde{\phi}$$

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

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

[Rattazzi, PhD thesis; Grzadkowski et al. NPB '04; JAAS NPB '09]

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 $\quad (x_b = m_b/mt,\, x_W = M_W/m_t)$

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

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

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

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

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

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

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

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

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,

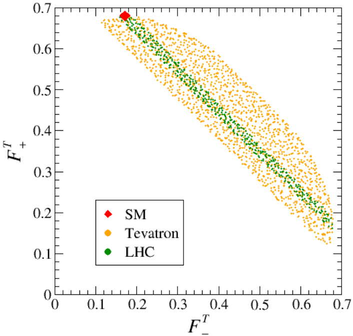
$$F_+^N = F_-^N = \frac{1}{2} - \frac{1}{4}(F_+ + F_-)$$

for CP-conserving *Wtb* vertex

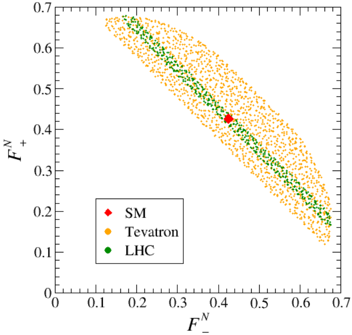
Indirect limits on $F_\pm^T$, $F_\pm^N$

Limits from helicity fractions $\oplus$ single top xsec

transverse



normal



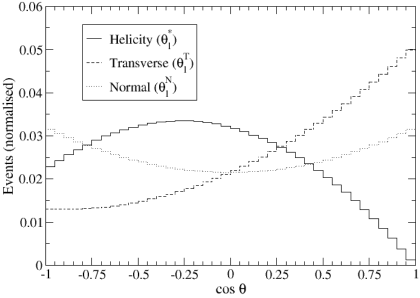
☞ ample room for departures from SM

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

How to measure?

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

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



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:

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

- ★ $F_+^N = F_-^N$ in the SM and for real *Wtb* vertex
- ★ FB asymmetry in $\cos\theta_\ell^N$ distribution $\quad A_{\mathrm{FB}}^N = \frac{3}{4}\left[F_+^N - F_-^N\right]$
  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]

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

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

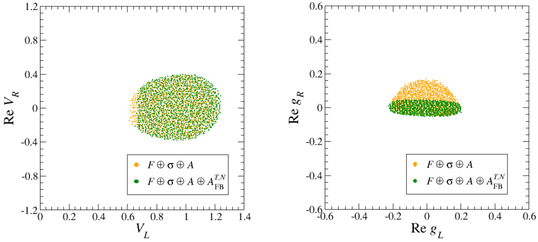
Highlights (III): The global fit

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

1. helicity fractions
2. the tW single top cross section
3. asymmetries in top rest frame and FB asymmetries $A_{\mathrm{FB}}^{T,N}$ in t-channel single top production

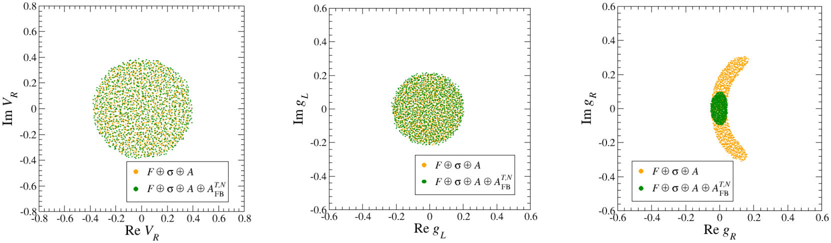
☞ single top polarisation P is taken as a free parameter and extracted from the fit

The global fit – results



$$P = [0.83 - 1]$$

(input $P = 0.9$)



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

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

Additional Slides

Operators involving top trilinear interactions

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

$$O_{Du}^{ij} = (\bar{q}_{Li} \, D_\mu u_{Rj}) \, D^\mu \, \tilde{\phi}$$
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$$O_{Dd}^{ij} = (\bar{q}_{Li} \, D_\mu d_{Rj}) \, D^\mu \, \phi$$
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[Buchmuller, Wyler NPB '86]

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redundants dropped

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

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redundants dropped

[JAAS NPB '09]

Operators involving top trilinear interactions

$$O_{\phi q}^{(3,i+j)} = 1/2\,[O_{\phi q}^{(3,ij)} + (O_{\phi q}^{(3,ji)})^\dagger] \quad i \le j$$
$$O_{\phi q}^{(1,i+j)} = 1/2\,[O_{\phi q}^{(1,ij)} + (O_{\phi q}^{(1,ji)})^\dagger] \quad i \le j$$
$$O_{\phi\phi}^{ij} = i(\tilde\phi^\dagger D_\mu \phi)(\bar u_{Ri}\gamma^\mu d_{Rj})$$
$$O_{\phi u}^{i+j} = 1/2\,[O_{\phi u}^{ij} + (O_{\phi u}^{ji})^\dagger] \quad i \le j$$
$$O_{uW}^{ij} = (\bar q_{Li}\sigma^{\mu\nu}\tau^I u_{Rj})\tilde\phi\, W_{\mu\nu}^I$$
$$O_{dW}^{ij} = (\bar q_{Li}\sigma^{\mu\nu}\tau^I d_{Rj})\phi\, W_{\mu\nu}^I$$
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$$O_{uG\phi}^{ij} = (\bar q_{Li}\lambda^a\sigma^{\mu\nu} u_{Rj})\tilde\phi\, G_{\mu\nu}^a$$
$$O_{u\phi}^{ij} = (\phi^\dagger\phi)(\bar q_{Li} u_{Rj}\tilde\phi)$$

$$O_{Du}^{ij} = (\bar q_{Li} D_\mu u_{Rj})\, D^\mu\, \tilde\phi$$
$$O_{\bar D u}^{ij} = (D_\mu \bar q_{Li}\, u_{Rj})\, D^\mu\, \tilde\phi$$
$$O_{Dd}^{ij} = (\bar q_{Li} D_\mu d_{Rj})\, D^\mu\, \phi$$
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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

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

$$\begin{aligned} O_{qG}^{ij} + (O_{qG}^{ji})^\dagger &= \frac{g_s}{2} O_{qq}^{(8,1,ijkk)} - \frac{8g_s}{9} O_{qu}^{(1,ikkj)} + \frac{g_s}{6} O_{qu}^{(8,ikkj)} - \frac{8g_s}{9} O_{qd}^{(1,ikkj)} \\ &\quad + \frac{g_s}{6} O_{qd}^{(8,ikkj)} \\ O_{uG}^{ij} + (O_{uG}^{ji})^\dagger &= -\frac{8g_s}{9} O_{qu}^{(1,kjik)} + \frac{g_s}{6} O_{qu}^{(8,kjik)} + g_s O_{uu}^{(1,ikkj)} - \frac{g_s}{3} O_{uu}^{(1,ijkk)} \\ &\quad + \frac{g_s}{4} O_{ud}^{(8,ijkk)} \end{aligned}$$

Technical details for fans

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

dual fields & quark EOM & Bianchi

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

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

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

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

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

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

int. by parts & scalar EOM

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

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

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

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

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

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

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

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

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

$$O_{lq}^{(1,ijkl)} = (\bar{l}_{Li}\gamma^\mu l_{Lj})(\bar{q}_{Lk}\gamma_\mu q_{Ll}) \qquad O_{lq}^{(3,ijkl)} = (\bar{l}_{Li}\gamma^\mu \tau^I l_{Lj})(\bar{q}_{Lk}\gamma_\mu \tau^I q_{Ll})$$

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

$$O_{ud}^{(1,ijkl)} = (\bar{u}_{Ri}\gamma^\mu u_{Rj})(\bar{d}_{Rk}\gamma_\mu d_{Rl}) \qquad O_{ud}^{(8,ijkl)} = (\bar{u}_{Ri}\gamma^\mu \lambda^a u_{Rj})(\bar{d}_{Rk}\gamma_\mu \lambda^a d_{Rl})$$

$$O_{lu}^{ijkl} = (\bar{l}_{Li} u_{Rj})(\bar{u}_{Rk} l_{Ll}) \qquad O_{qe}^{ijkl} = (\bar{q}_{Li} e_{Rj})(\bar{e}_{Rk} q_{Ll})$$

$$O_{qu}^{(1,ijkl)} = (\bar{q}_{Li} u_{Rj})(\bar{u}_{Rk} q_{Ll}) \qquad O_{qu}^{(8,ijkl)} = (\bar{q}_{Li}\lambda^a u_{Rj})(\bar{u}_{Rk}\lambda^a q_{Ll})$$

$$O_{qd}^{(1,ijkl)} = (\bar{q}_{Li} d_{Rj})(\bar{d}_{Rk} q_{Ll}) \qquad O_{qd}^{(8,ijkl)} = (\bar{q}_{Li}\lambda^a d_{Rj})(\bar{d}_{Rk}\lambda^a q_{Ll})$$

$$O_{qde}^{ijkl} = (\bar{l}_{Li} e_{Rj})(\bar{d}_{Rk} q_{Ll}) \qquad O_{qq}^{(1,ijkl)} = (\bar{q}_{Li} u_{Rj})\,\left[(\bar{q}_{Lk}\epsilon)^T d_{Rl}\right]$$

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

A minimal set of top anomalous couplings

Wtb vertex - before

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

A minimal set of top anomalous couplings

Wtb vertex - without redundant operators

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

Operator contributions to top vertices

Contributions to *Wtb* vertex

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

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

Four-fermion operators and single top

Four-fermion operators contributing to single top (t, s-channel)

(i, j, k, l are flavour indices)

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

$$O_{ud}^{(1,ijkl)} = (\bar u_{Ri}\gamma^\mu u_{Rj})(\bar d_{Rk}\gamma_\mu d_{Rl}) \qquad O_{ud}^{(8,ijkl)} = (\bar u_{Ri}\gamma^\mu \lambda^a u_{Rj})(\bar d_{Rk}\gamma_\mu \lambda^a d_{Rl})$$

$$O_{qu}^{(1,ijkl)} = (\bar q_{Li} u_{Rj})(\bar u_{Rk} q_{Ll}) \qquad O_{qu}^{(8,ijkl)} = (\bar q_{Li}\lambda^a u_{Rj})(\bar u_{Rk}\lambda^a q_{Ll})$$

$$O_{qd}^{(1,ijkl)} = (\bar q_{Li} d_{Rj})(\bar d_{Rk} q_{Ll}) \qquad O_{qd}^{(8,ijkl)} = (\bar q_{Li}\lambda^a d_{Rj})(\bar d_{Rk}\lambda^a q_{Ll})$$

$$O_{qq}^{(1,ijkl)} = (\bar q_{Li} u_{Rj})([\bar q_{Lk}\epsilon]^T d_{Rl}) \qquad O_{qq}^{(8,ijkl)} = (\bar q_{Li}\lambda^a u_{Rj})([\bar q_{Lk}\epsilon]^T \lambda^a d_{Rl})$$

10 for $ub \to dt$
10 for $cb \to st$
➞ total $=$ 20 operators

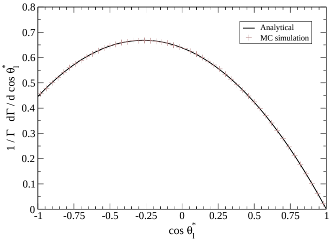
If you think I'm missing four-fermion operators note that, for example

$$\begin{aligned} O_{qq}^{(1,3,ijkl)} &\equiv \frac{1}{2} (\bar{q}_{Li} \gamma^\mu \tau^I q_{Lj})(\bar{q}_{Lk} \gamma_\mu \tau^I q_{Ll}) \\ &= \frac{2}{3} O_{qq}^{(1,1,ilkj)} + O_{qq}^{(8,1,ilkj)} - O_{qq}^{(1,1,ijkl)} \\ O_{qq}^{(8,3,ijkl)} &\equiv \frac{1}{2} (\bar{q}_{Li} \gamma^\mu \lambda^a \tau^I q_{Lj})(\bar{q}_{Lk} \gamma_\mu \lambda^a \tau^I q_{Ll}) \\ &= \frac{32}{9} O_{qq}^{(1,1,ilkj)} - O_{qq}^{(8,1,ijkl)} - \frac{2}{3} O_{qq}^{(8,1,ilkj)} \end{aligned}$$

using λ^a, τ^I completeness relations and Fierz rearrangements

☞ several four-fermion operators in BW list are redundant

W helicity fractions and related observables

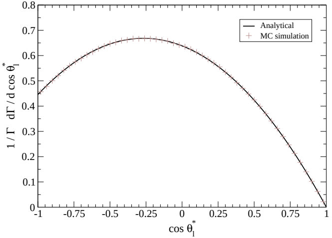


[JAAS et al. EPJC '07,08]

W helicity fractions and related observables

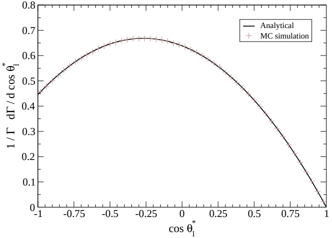
fit → F_0, F_-, F_+

(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_+

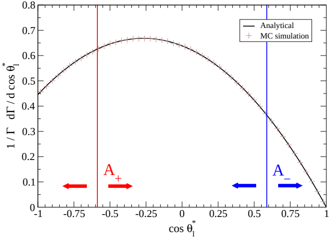
(with $F_0 + F_- + F_+ = 1$)

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

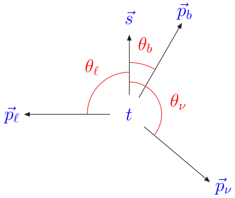
A_+ ☞ best limit on g_R

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]