Precise determination of the Wtb couplings at LHC

[F. del Aguila, JAAS]

In the SM: $V_{tb} \gg V_{td}, V_{ts}$

$$\left.\begin{array}{l} \text{- } t\bar{t} \text{ cross-section independent of } V_{tb} \\ \text{- } t \to Wb \text{ practically independent} \end{array}\right\} \Rightarrow \begin{array}{l} V_{tb} \text{ cannot be measured in } t\bar{t} \text{ production} \end{array}$$

Single top cross-section $\propto |V_{tb}|^2 \Rightarrow$ Measurement of V_{tb} at LHC

Is $t\bar{t}$ production useless to measure V_{tb}?

The answer is: NO

$t\bar{t}$ production is very sensitive to small admixtures of other Wtb couplings

$$\mathcal{L} = \frac{g}{\sqrt{2}} \bar{t} \, \gamma^\mu \left(V_{tb}^L P_L + V_{tb}^R P_R \right) b \, W_\mu^+ + \frac{g}{\sqrt{2}} \bar{t} \, \frac{i \sigma^{\mu\nu} q_\nu}{M_W} \left(g^L P_L + g^R P_R \right) b \, W_\mu^+ + \text{h.c.}$$

Angular asymmetries can measure the values of V_{tb}^R, g^L, g^R relative to V_{tb}^L

(from now on, normalise V_{tb}^L to 1)

How do these couplings appear?

QCD corrections to $t \to Wb$ generate
$g^R = -0.00642$ at 1 loop

$\left[\begin{array}{l}\text{Li, Oakes, Yuan} \\ \text{PRD 43, 3759 (1991)}\end{array}\right]$

This can be seen with 6σ statistical significance at LHC

Models beyond the SM (SUSY, extra gauge bosons, etc.) give new contributions to g^R, g^L, V_{tb}^R, that may well be as large as this one (at least) and <u>should</u> be seen if they do not unnaturally cancel.

Limits from low energy physics

$b \to s\gamma$ sets limit $V_{tb}^R \leq 0.04$

[Larios, Perez, Yuan
PLB 457, 334 (1999)]

But:
- Limit assumes $V_{ts} = 0.04$
- Unclear that $\Gamma(b \to s\gamma)$ comes from top diagram

V_{tb}^R, g^R in principle influence

LEP precision observables

But: Their contribution is proportional to

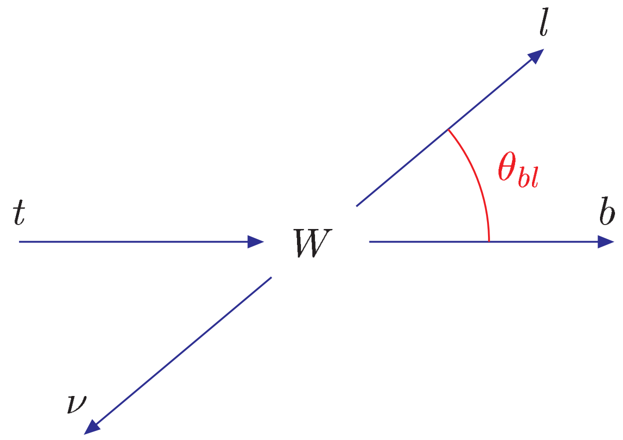
$m_b \ll m_t$ and hence negligible

[Whisnant *et al.*
PRD 56, 467 (1997)]

$$\left.\begin{array}{ll} - & \text{No limits from} \\ & \text{low energies} \\ - & \text{Observable} \\ & \text{predictions} \\ & \text{for SM and} \\ & \text{extensions} \end{array}\right\} \Rightarrow \begin{array}{l} \text{It is very important} \\ \text{to measure these} \\ \text{couplings} \end{array}$$

FB asymmetry in the W rest frame

$$\left[\begin{array}{l}\text{Lampe}\\ \text{NPB 454, 506 (1995)}\end{array}\right]$$



$$x_{bl} = \cos\theta_{bl}$$

$$A_{\text{FB}} = \frac{N(x_{bl} > 0) - N(x_{bl} < 0)}{N(x_{bl} > 0) + N(x_{bl} < 0)}$$

(Compare with FB asymmetry at LEP)

Spin correlation observables in $t\bar{t}$ production

Top quarks are produced whithout net polarization but $t\bar{t}$ pairs have their spins correlated

Correlations:

[Brandenburg PLB 388, 626 (1996)]

$(\hat{\mathbf{k}}_t \cdot \mathbf{s}_t)\,(\hat{\mathbf{k}}_{\bar{t}} \cdot \mathbf{s}_{\bar{t}})$ $\rightarrow$ Correlation in helicity basis

$(\mathbf{s}_t \cdot \mathbf{s}_{\bar{t}})$

$(\hat{\mathbf{k}} \cdot \mathbf{s}_t)\,(\hat{\mathbf{k}} \cdot \mathbf{s}_{\bar{t}})$ $\rightarrow$ Correlation in beam line basis

$(\hat{\mathbf{k}} \cdot \mathbf{s}_t)\,(\hat{\mathbf{k}}_{\bar{t}} \cdot \mathbf{s}_{\bar{t}}) + (\hat{\mathbf{k}}_t \cdot \mathbf{s}_t)\,(\hat{\mathbf{k}} \cdot \mathbf{s}_{\bar{t}})$ $\rightarrow$ Mixed basis

$\hat{\mathbf{k}}_t$: top momentum in CM system

$\hat{\mathbf{k}}_{\bar{t}}$: antitop momentum in CM system

$\hat{\mathbf{k}}$: unit vector in the direction of the beam

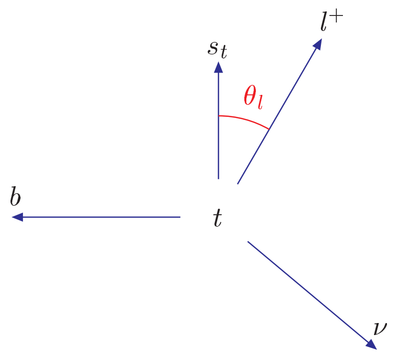
Best basis: helicity basis (largest correlation)

[Mahlon, Parke PRD 53, 4886 (1996)]

Spin of $t, \bar{t}$ is not directly observable

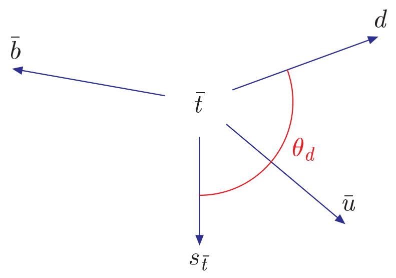
$\rightarrow$ inferred through angular distributions of decay products

Top decay (in top rest frame)



$$\frac{d\Gamma}{d\cos\theta_i} = \frac{1}{2}(1 + h_i \cos\theta_i)$$

Antitop decay (in antitop rest frame)



$$\frac{d\Gamma}{d\cos\theta_i} = \frac{1}{2}(1 - h_i \cos\theta_i)$$

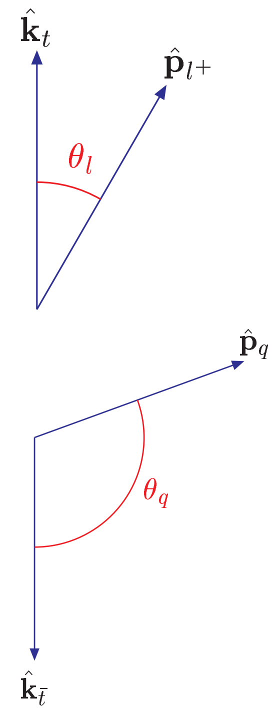
Spin correlation asymmetries

$\hat{\mathbf{k}}_t$ top momentum in CM system

$\hat{\mathbf{k}}_{\bar{t}}$ antitop momentum in CM system

$\hat{\mathbf{p}}_{l^+}$ l^+ momentum in top rest frame

$\hat{\mathbf{p}}_q$ l.e.j. momentum in antitop rest frame



$x_l = \cos\theta_l$, $x_q = \cos\theta_q$

$$A_1 = \frac{N(x_l x_q > 0) - N(x_l x_q < 0)}{N(x_l x_q > 0) + N(x_l x_q < 0)}$$

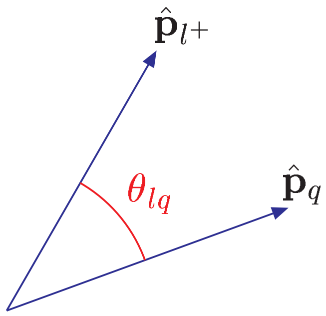
[Stelzer, Willenbrock
PLB 374, 169 (1996)]

[Lots of more people]

From $(\mathbf{s}_t \cdot \mathbf{s}_{\bar{t}})$

$\hat{\mathbf{p}}_{l+}$ l^+ momentum in top rest frame

$\hat{\mathbf{p}}_q$ l.e.j. momentum in antitop rest frame



$x_{lq} = \cos\theta_{lq}$

$$A_2 = \frac{N(x_{lq} > 0) - N(x_{lq} < 0)}{N(x_{lq} > 0) + N(x_{lq} < 0)}$$

Advantage: only one angle

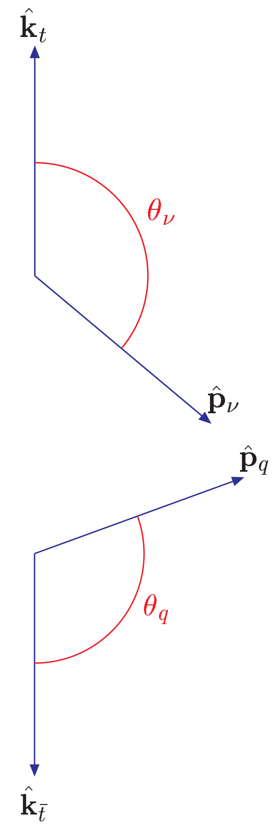
Also,

$\hat{\mathbf{k}}_t$ top momentum in CM system

$\hat{\mathbf{k}}_{\bar{t}}$ antitop momentum in CM system

$\hat{\mathbf{p}}_\nu$ ν momentum in top rest frame

$\hat{\mathbf{p}}_q$ l.e.j. momentum in antitop rest frame



$x_\nu = \cos\theta_\nu, \; x_q = \cos\theta_q$

$$A_3 = \frac{N(x_\nu x_q > 0) - N(x_\nu x_q < 0)}{N(x_\nu x_q > 0) + N(x_\nu x_q < 0)}$$

[Jeżabek, Kühn
PLB 329, 317 (1994)]

Spin correlations asymmetries depend on the production mechanism:

$$A_1 \sim \frac{1}{4} C h_l h_q$$

where

$$C = \frac{N(t_L\bar{t}_L) + (t_R\bar{t}_R) - (t_L\bar{t}_R) - (t_R\bar{t}_L)}{N(t_L\bar{t}_L) + (t_R\bar{t}_R) + (t_L\bar{t}_R) + (t_R\bar{t}_L)}$$

C depends on the production mechanism ($u\bar{u}$, gg), on the CM energy, and (worse): on the presence of anomalous $gt\bar{t}$ couplings in the production

$C = 0.31$ at LHC

Analytical expression of A_{FB}

$$
\begin{aligned}
\mathcal{N} &= 3\, q_b \left[-2 \left({g^L}^2 - {g^R}^2 \right) E_b \right. \\
&\quad + \left({V_{tb}^L}^2 - {V_{tb}^R}^2 - {g^L}^2 + {g^R}^2 \right) M_W \\
&\quad - 2\, V_{tb}^L \left(g^L\, m_b + g^R\, m_t \right) \\
&\quad \left. + 2\, V_{tb}^R \left(g^R\, m_b + g^L\, m_t \right) \right]
\end{aligned}
$$

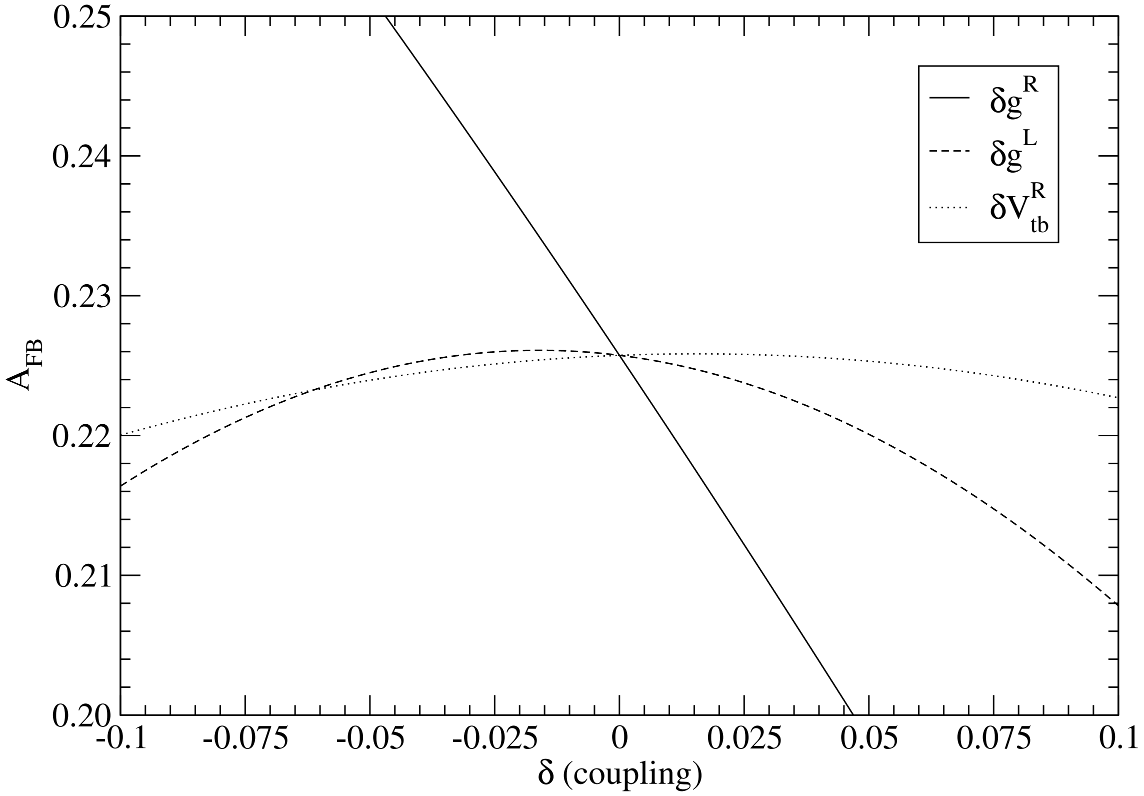
$$
\begin{aligned}
\mathcal{D} &= 2 \left[\left({g^L}^2 + {g^R}^2 \right) \left(4\, {q_b}^2 + 3\; E_b\, M_W \right) \right. \\
&\quad + \left({V_{tb}^L}^2 + {V_{tb}^R}^2 \right) \left(2\, {E_b}^2 + {m_b}^2 + 3\, E_b\, M_W \right) \\
&\quad - 6 \left(g^L\, g^R + V_{tb}^L\, V_{tb}^R \right) m_b\, m_t \\
&\quad + 6 \left(V_{tb}^L\, g^L + V_{tb}^R\, g^R \right) \left(E_b + M_W \right) m_b \\
&\quad \left. - 6 \left(V_{tb}^L\, g^R + V_{tb}^R g^L \right) E_b\, m_t \right]
\end{aligned}
$$

Simple analysis of A_{FB} (using analytical expression)

$\delta g^R \equiv g^R + 0.00642$

$\delta g^L \equiv g^L$

$\delta V_{tb}^R \equiv V_{tb}^R$



Sensitivitiy to δg^R: excellent

Sensitivity to δg^L,δV_{tb}^R: good

Tree-level: $A_{\mathsf{FB}} = 0.2223$

With QCD corrections: $A_{\mathsf{FB}} = 0.2257$

Numerical analysis of A_{FB}

Matrix element:

$$gg,\ q\bar{q} \to t\bar{t} \to W^+ b W^- \bar{b} \to l\nu b q \bar{q}' \bar{b}$$

$\left[\begin{array}{l}\text{MadGraph} \\ \text{HELAS}\end{array}\right]$

$+$ $\sigma^{\mu\nu}$ vertex for QCD corrections and anomalous couplings

$\left.\begin{array}{l} A \propto N_+ - N_- \\ \text{with } N_+ \sim N_- \end{array}\right\} \Rightarrow$ Good MC statistics needed

To detect small differences in A $\Rightarrow$ Very good MC statistics needed

We generate 200M real $t\bar{t} \to l\nu b q \bar{q}' \bar{b}$ events per channel μ, e (70 times more than the number at LHC)

Important: The same events for each evaluation of the asymmetry

Check

Assumming complete particle identification and perfect momenta reconstruction (even ν)

Tree-level: $A_{\mathrm{FB}} = 0.2222$
With QCD corrections: $A_{\mathrm{FB}} = 0.2257$

(Compare with $A_{\mathrm{FB}} = 0.2223$, $A_{\mathrm{FB}} = 0.2257$ from the analytical calculation)

$A_1 = -0.0835$

(Compare with $A_1 = -0.082$)

[Mahlon, Parke
PRD 53, 4886 (1996)]

Simple detector simulation

$$\frac{\Delta E^j}{E^j} = \frac{50\%}{\sqrt{E^j}} \oplus 3\%$$

$$\frac{\Delta E^e}{E^e} = \frac{10\%}{\sqrt{E^e}} \oplus 0.3\%$$

$$\frac{\Delta E^\mu}{E^\mu} = 2.5\%$$

Usual trigger conditions for Run H

(in practice, $p_T^e \geq 30$, $p_T^\mu \geq 20$)

Influence of the background

In each hemisphere: n events observed
b $Wjjjj$ background events

$\rightarrow$ confidence interval for the signal

For large $n, b \rightarrow$ Gaussian approximation is good
$\rightarrow$ Signal $= (n - b) \pm \sqrt{n}$

Or, defining $s \equiv n - b$,
Signal $= s \pm \sqrt{s + b}$

Therefore, it is convenient to reduce b (as usual)

Cuts

$$\begin{array}{ccccc} 130 & \leq & m_t^{\text{rec}} & \leq & 220 \\ 150 & \leq & m_{\bar{t}}^{\text{rec}} & \leq & 200 \\ 65 & \leq & M_{W^-}^{\text{rec}} & \leq & 95 \end{array}$$

Signal and background

		$l = \mu$		$l = e$	
		$t\bar{t}$	$Wjjjj$	$t\bar{t}$	$Wjjjj$
A_{FB}	N_+	16.064	2.62	12.230	2.99
	N_-	11.874	2.59	11.012	2.42
A_1	N_+	13.641	2.51	11.546	2.66
	N_-	14.297	2.71	11.696	2.74
A_2	N_+	14.526	2.82	11.908	2.94
	N_-	13.412	2.40	11.334	2.46
A_3	N_+	13.955	2.62	11.552	2.67
	N_-	13.983	2.59	11.690	2.73

$\delta A \simeq 6.5 \times 10^{-4}$ muon channel

$\delta A \simeq 7.2 \times 10^{-4}$ electron channel

Asymmetries

Coupling	l	A_{FB}	A_1	A_2	A_3
SM tree-level	μ	0.1470	-0.0236	0.0398	-0.0013
SM tree-level	e	0.0496	-0.0064	0.0247	-0.0061
SM	μ	0.1499	-0.0235	0.0399	-0.0010
SM	e	0.0524	-0.0064	0.0247	-0.0059
$\delta g^R = 0.003$	μ	0.1486	-0.0236	0.0398	-0.0011
$\delta g^R = 0.003$	e	0.0511	-0.0064	0.0247	-0.0060
$\delta g^R = -0.003$	μ	0.1513	-0.0235	0.0399	-0.0009
$\delta g^R = -0.003$	e	0.0537	-0.0064	0.0247	-0.0058
$\delta g^L = 0.02$	μ	0.1486	-0.0236	0.0399	-0.0010
$\delta g^L = 0.02$	e	0.0510	-0.0065	0.0248	-0.0059
$\delta g^L = -0.05$	μ	0.1487	-0.0234	0.0395	-0.0011
$\delta g^L = -0.05$	e	0.0512	-0.0062	0.0243	-0.0060
$\delta V_{tb}^R = 0.08$	μ	0.1485	-0.0232	0.0392	-0.0010
$\delta V_{tb}^R = 0.08$	e	0.0510	-0.0061	0.0241	-0.0059
$\delta V_{tb}^R = -0.04$	μ	0.1488	-0.0234	0.0395	-0.0010
$\delta V_{tb}^R = -0.04$	e	0.0512	-0.0062	0.0243	-0.0059

Statistical significance

Coupling	A_{FB}	A_1	A_2	A_3
SM tree-level	6.0σ	0.1σ	0.0σ	0.5σ
$\delta g^R = 0.003$	2.8σ	0.1σ	0.0σ	0.2σ
$\delta g^R = -0.003$	2.8σ	0.0σ	0.0σ	0.2σ
$\delta g^L = 0.02$	2.9σ	0.2σ	0.1σ	0.1σ
$\delta g^L = -0.05$	2.5σ	0.4σ	0.8σ	0.1σ
$\delta V_{tb}^R = 0.08$	3.0σ	0.7σ	1.3σ	0.0σ
$\delta V_{tb}^R = -0.04$	2.5σ	0.3σ	0.7σ	0.1σ

$\rightarrow$ A_{FB} far better than A_{1-3}
to measure the Wtb vertex

(and A_{1-3} also depend on the production process)

Conclusions

- It is very important to measure the Wtb vertex
- It can be done at LHC
- The FB asymmetry in $t\bar{t}$ production does the job for anomalous couplings
- Single top production measures the 'overall constant'
- The FB asymmetry analysis turns the spin correlation asymmetries sensitive only to anomalous production processes