New angles on top decay to a charged Higgs

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with D. Eriksson, G. Ingelman, and J. Rathsman
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Top quarks

There are several reasons why the top quark is special:

- It is the heaviest particle in the SM
- Since $\Gamma_t \gg \Lambda_{\rm QCD}$, t decays without forming hadrons
- Large top Yukawa coupling $y_t = v/(\sqrt{2}m_t) \simeq 1$ connects top to EWSB
- All its expected properties are not yet verified by experiment

At the LHC, top quarks will be produced in large quantities $\sigma(pp \to t\bar{t}) \simeq 900$ pb @ NLO for $m_t = 170.9$ GeV $\Rightarrow$

- More precise measurements of mass and cross section
- Spin correlations
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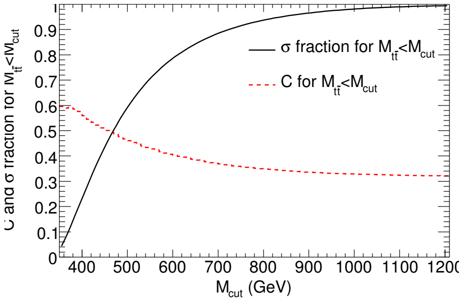
- Hadroproduction of $t\bar{t}$ is a modern version of an EPR experiment: Knowing the spin of one t statistically predicts the spin of the other.
- Overall correlation $\mathcal{C} = \left\langle (\overline{S}_t \cdot \hat{a})(\overline{S}_{\bar{t}} \cdot \hat{b}) \right\rangle$ obtained by weighting partonic correlations with pdfs.
- At the LHC, where $gg \to t\bar{t}$ dominates, $\mathcal{C} = 0.326$ in the helicity basis, while at the Tevatron $\mathcal{C} = -0.352$ (mostly $q\bar{q}$)



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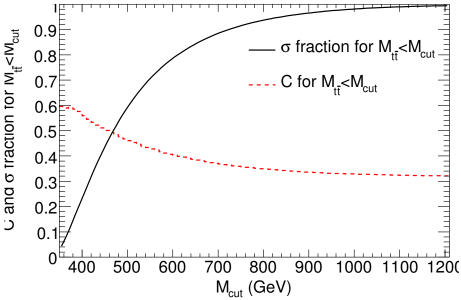

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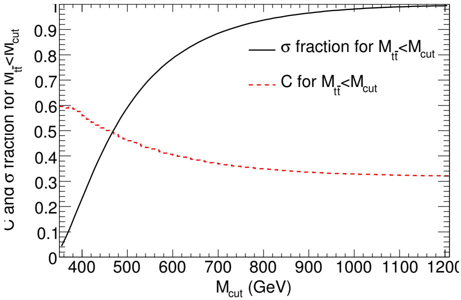

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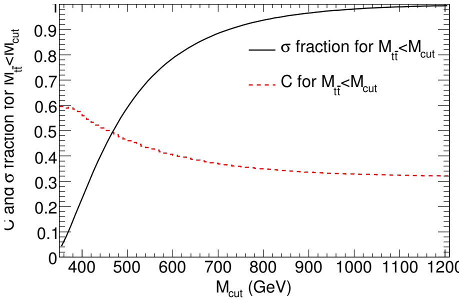

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Analyzing the top spin

- The V-A vertex for the weak top decay

$$\mathcal{L}_{Wtb} = \frac{g_W}{\sqrt{2}} V_{tb} W_\mu^+ \bar{t} \gamma^\mu \frac{1-\gamma^5}{2} b + h.c.$$

is parity violating and analyzes the spin of the decaying quark.

- Decay of polarized particles:

$$\frac{1}{\Gamma}\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta_i} = \frac{1+\alpha_i\cos\theta_i}{2}$$

Spin projection $\cos\theta_i$ defined in decay rest frame. *Spin analyzing coefficient* α_i for each decay product.

- Example: $t_\uparrow \to bW^+ \to bl^+\nu_l$ with $\alpha_l = 1.0$, $\alpha_{\nu_l} = -0.35$, $\alpha_W = -\alpha_b = 0.4$

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$$\frac{1}{N}\frac{\mathrm{d}^2 N}{\mathrm{d}\cos\theta_i \mathrm{d}\cos\theta_j} = \frac{1}{4}\left(1 + \mathcal{C}\alpha_i\alpha_j \cos\theta_i \cos\theta_j\right)$$

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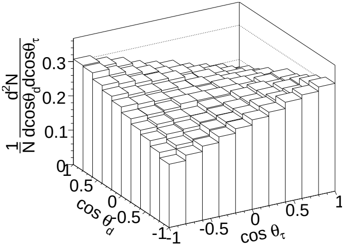

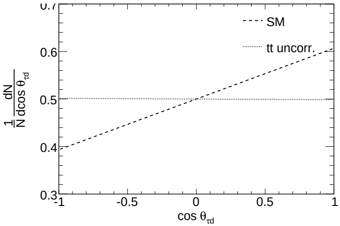

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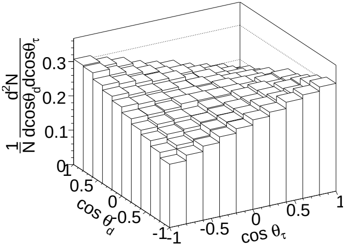

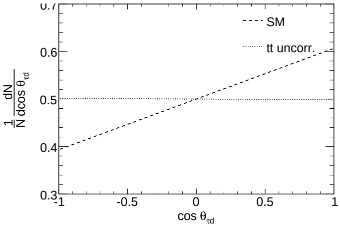

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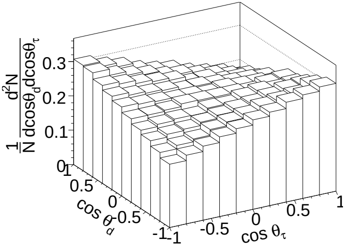

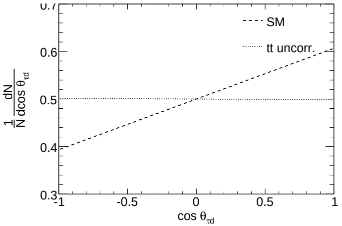

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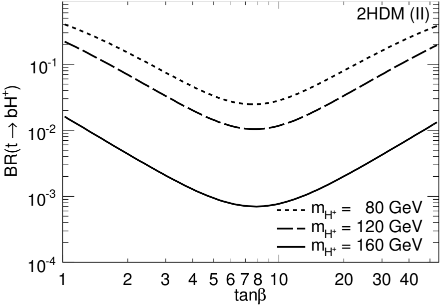
Top decay through $H^{\pm}$

- In models with a sufficiently light $H^{\pm}$, the decay $t \to bH^{+}$ can occur with possibly quite large $\mathcal{BR}(t \to bH^{+})$



- The vertex has a different form compared to the tbW^{+} V-A:

$$\mathcal{L}_H = \frac{g_W}{2\sqrt{2}m_W} V_{tb} H^{+} \bar{t} \Big[A(1-\gamma_5) + B(1+\gamma_5) \Big] b + h.c.$$

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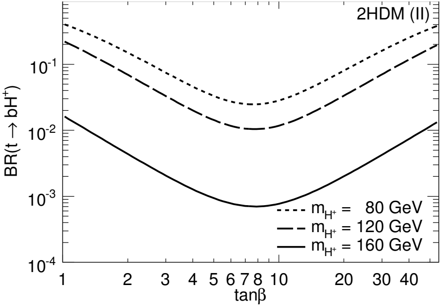

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Spin analyzing coefficients

- Spin analyzing coefficients α_i for polarized top decay:

Analyzer	Channel: W ($\omega = m_W^2/m_t^2$)	Channel: H ($\xi = m_H^2/m_t^2$)
b	$-\frac{1-2\omega}{1+2\omega}$	$-\frac{A^2-B^2}{A^2+B^2} f(\xi, A, B)$
W^+/H^+	$\frac{1-2\omega}{1+2\omega}$	$\frac{A^2-B^2}{A^2+B^2} f(\xi, A, B)$
l^+ ($\bar{d}$)	1	$\frac{1-\xi^2+2\xi\ln\xi}{(1-\xi)^2}\frac{A^2-B^2}{A^2+B^2} f(\xi, A, B)$
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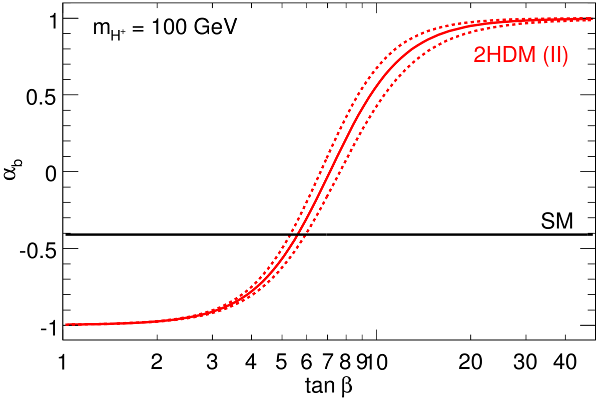
- The ratio $A^2 - B^2/(A^2 + B^2)$ is important



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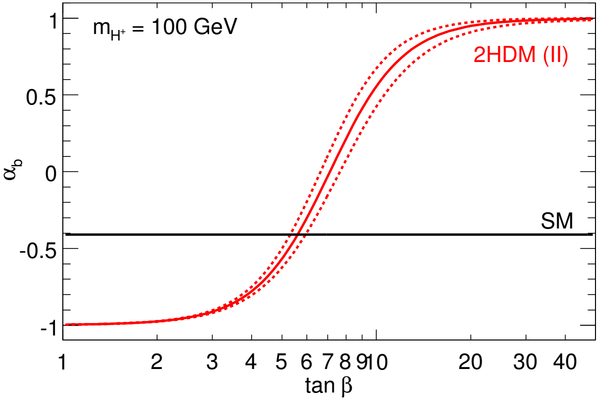

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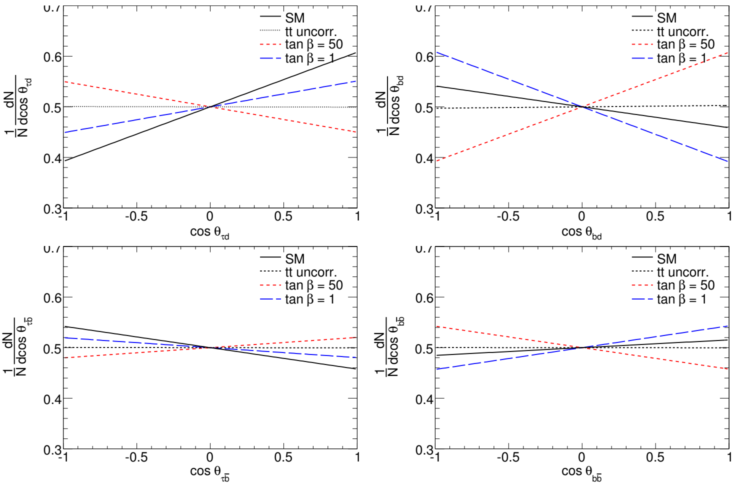
Matrix Element Results

- Angular distributions $\cos\Theta_{ij}$ for SM and 2HDM (II), $m_{H^+} = 80$ GeV

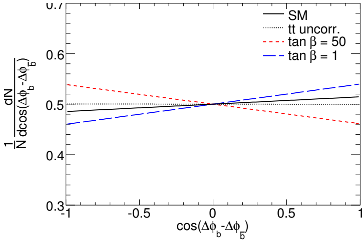


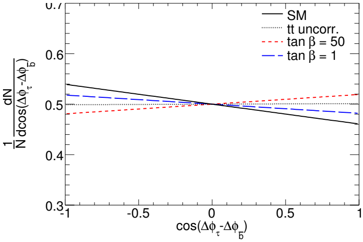
Transverse correlations

- $H^\pm$ decays to $\tau^\pm\nu_\tau$
  $\Rightarrow$ Not possible to find rest frames for $t(\bar{t})$
- Solution is to look at correlations in the transverse plane which are accessible in all-hadronic channel

$$\frac{\mathrm{d}N}{\mathrm{d}\cos(\Delta\phi_i-\Delta\phi_j)}=\frac{1}{2}\Big(1+\mathcal{D}'\alpha_i\alpha_j\cos(\Delta\phi_i-\Delta\phi_j)\Big)$$

- Numerically we find $\mathcal{D}'\simeq 0.9\mathcal{D}$, i.e. correlation almost as strong as before. Only bb and τb angles can be reconstructed unambigiously (low d-jet tagging eff.)





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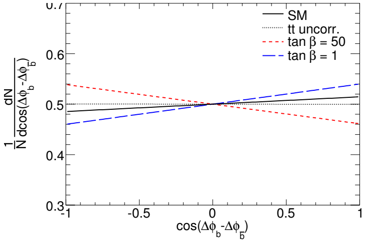

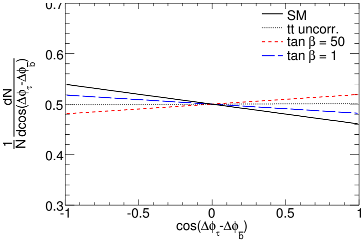

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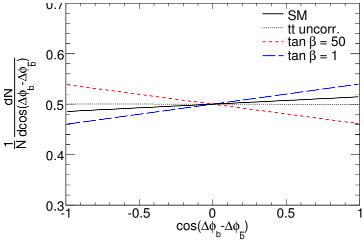
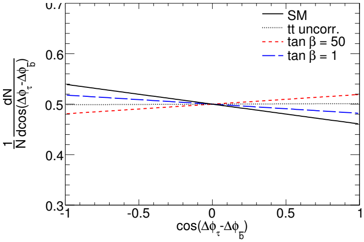
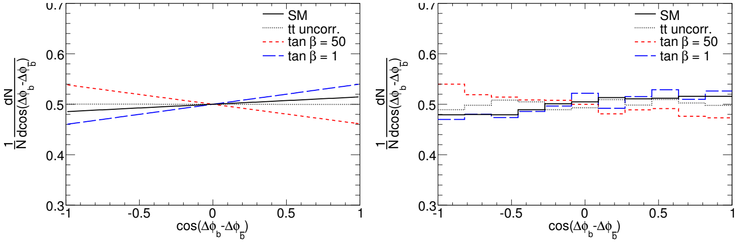




Hadron level Results

- Hadron level simulation: $2 \to 6$ ME from MadEvent, Pythia for parton showering, hadronization and underlying event
- Jet reconstruction with exclusive $k_\perp$ alg., $d_{\rm cut} = 400$ GeV^2
  Simplistic flavour tagging $\Delta R(\mathrm{jet}, \mathrm{parton}) < 0.4$, $|\eta| < 2.5$
  Mass windows for reconstructed W (10 GeV) and t (15 GeV)
  Histograms normalized to one



- Effects are still there, hadronization and jet effects small
  Somewhat limited by statistics
- Hadron level results for τb are similar

Summary and Outlook

- We have studied $t\bar{t}$ spin correlation measurements and the decay $t \to bH^+ \to b\tau^+\nu_\tau$
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- The decay $H^\pm \to \tau^\pm\nu_\tau$ requires new analysis using transverse correlations
- For the future (along these lines):
  - Complete event simulation
  - SM $t\bar{t}$ spin correlations, transverse correlations
  - Using transverse rest frame to measure spin
  - Effects of $\tau^\pm \to l^\pm\nu_l$ on di-lepton correlations
  - Obtain $H^\pm$ properties where discovery is feasible (light $H^\pm$)
- For LHC Physics analyses, I commit to providing theory input on the issues discussed here. If there is an interest, I would be very happy to collaborate with experimental colleagues.
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BACKUP

Cross section and correlations

CTEQ6.1 PDF, $\mu_R = \mu_F = m_t = 170.9$ GeV
$\sigma(pp \to t\bar{t} + X) \simeq 900$ pb at $\sqrt{s} = 14$ TeV

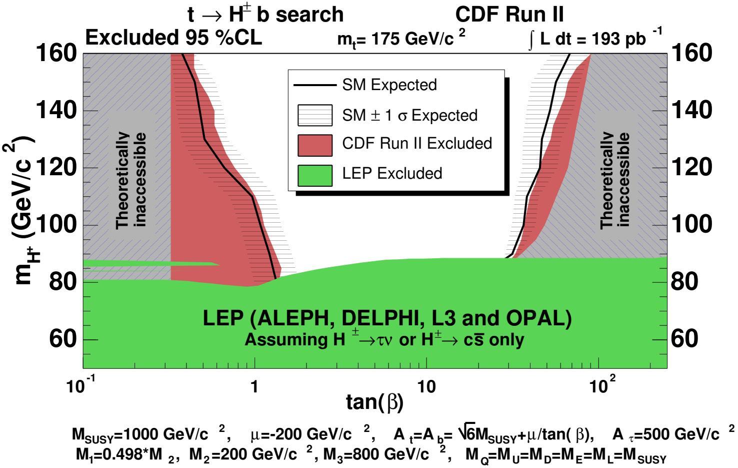
$$\hat{C}_{ij}(M^2_{t\bar{t}}) = \frac{\hat{\sigma}_{ij}(t_\uparrow \bar{t}_\uparrow + t_\downarrow \bar{t}_\downarrow) - \hat{\sigma}_{ij}(t_\downarrow \bar{t}_\uparrow + t_\uparrow \bar{t}_\downarrow)}{\hat{\sigma}_{ij}(t_\uparrow \bar{t}_\uparrow + t_\downarrow \bar{t}_\downarrow) + \hat{\sigma}_{ij}(t_\downarrow \bar{t}_\uparrow + t_\uparrow \bar{t}_\downarrow)}$$

$q\bar{q} \to t\bar{t}$: $\hat{C}(4m_t^2) = -1/3$
$gg \to t\bar{t}$: $\hat{C}(4m_t^2) = 1$
In the ultra-relativistic limit both $\hat{C} \to -1$

$$\mathcal{C}(s) = \frac{1}{\sigma_{t\bar{t}}} \sum_{i,j=\{q,\bar{q},g\}} \int \mathrm{d}x_1 \mathrm{d}x_2 \left[\hat{\sigma}_{ij}(t_\uparrow \bar{t}_\uparrow + t_\downarrow \bar{t}_\downarrow) - \hat{\sigma}_{ij}(t_\downarrow \bar{t}_\uparrow + t_\uparrow \bar{t}_\downarrow)\right] f_i(x_1, \mu_F^2) f_j(x_2, \mu_F^2)$$

At the LHC, $\mathcal{C} = 0.326$ at NLO

Light Charged Higgs Boson limits



Effective Lagrangian, matrix elements

$$\mathcal{L}_H = \frac{g_W}{2\sqrt{2}m_W} \sum_{\substack{\{u,c,t\}\\\{d,s,b\}}} V_{ud} \left\{ H^+ \bar{u}\left[A\,(1-\gamma_5) + B\,(1+\gamma_5)\right] d + H^- \bar{d}\left[B^*\,(1-\gamma_5) + A^*\,(1+\gamma_5)\right] u \right\}$$

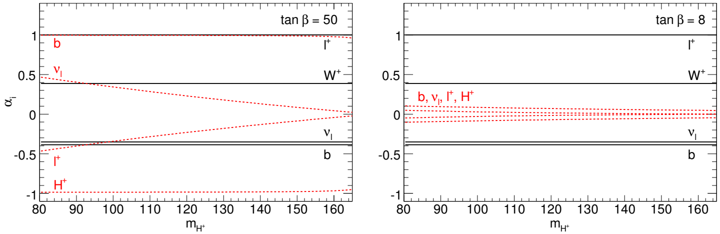
$$+ \frac{g_W}{2\sqrt{2}m_W} \sum_{\{e,\mu,\tau\}} \left[H^+ C \bar{\nu}_l\,(1+\gamma_5)\,l + H^- C^* \bar{l}\,(1-\gamma_5)\,\nu_l\right].$$

$$\rho^W_{\lambda\lambda'} = |\mathcal{M}_{\lambda\lambda'}(t \to bW^+ \to bl^+\nu_l)|^2 = \frac{2g_W^4 |V_{tb}|^2 (p\cdot k_2)(k_1\cdot k_3)}{(q^2 - m_W^2)^2 + m_W^2\Gamma_W^2}\left[\delta_{\lambda\lambda'} + \hat{k}_2^a \sigma^a_{\lambda\lambda'}\right]$$

$$\rho^H_{\lambda\lambda'} = |\mathcal{M}_{\lambda\lambda'}(t \to bH^+ \to bl^+\nu_l)|^2 = \frac{g_W^4 |V_{tb}|^2 (p\cdot k_1)(k_2\cdot k_3)}{(q^2 - m_{H^+}^2)^2 + m_{H^+}^2\Gamma_{H^+}^2}\frac{C^2(A^2+B^2)}{2m_W^4}$$

$$\times\left(1 + \frac{AB}{A^2+B^2}\frac{4\delta}{1-\xi}\right)\left[\delta_{\lambda\lambda'} - \frac{A^2-B^2}{A^2+B^2}\left(1+\frac{AB}{A^2+B^2}\frac{4\delta}{1-\xi}\right)^{-1}\hat{k}_1^a\sigma^a_{\lambda\lambda'}\right].$$

Spin analyzing coefficients - dependence on m_{H^+}



Generated event samples

Model		Number of events		
		Generated	Reconstructed	$\int \mathcal{L}$ (fb^{-1})
SM		804 926	46 524	11.7
$t\bar{t}$ uncorr.		937 552	54 280	13.7
2HDM (II)	$\tan\beta = 50$, $m_{H^+} = 80$ GeV	925 806	59 061	3.84
2HDM (II)	$\tan\beta = 1$, $m_{H^+} = 80$ GeV	926 690	59 068	7.77