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New angles on top quark decay to a charged Higgs

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based on work with D. Eriksson, G. Ingelman, and O. Stål

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The Higgs sector beyond the Standard Model

Why study Higgs sector at LHC?

- direct information about origin of electroweak symmetry breaking (EWSB)
- large variety of SM extensions with extended Higgs sector
- sensitive probe of underlying physics model (additional singlets or doublets, mass-relations, mixings and couplings)
- SM Higgs may be hidden

The Minimal Supersymmetric Standard Model (MSSM)

- Supersymmetry (SUSY) solves finetuning problem of SM ($\delta m_h^2 \propto M_{\rm planck}^2 \to \delta m_h^2 \propto M_{\rm SUSY}^2$)
- two Higgs doublets required by SUSY
- EWSB $\Rightarrow$ five Higgs bosons: h, H, A, H^+, H^-
- relatively simple (two parameters at tree-level, M_A and $\tan\beta = v_2/v_1$)

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Experimental constraints on Charged Higgs

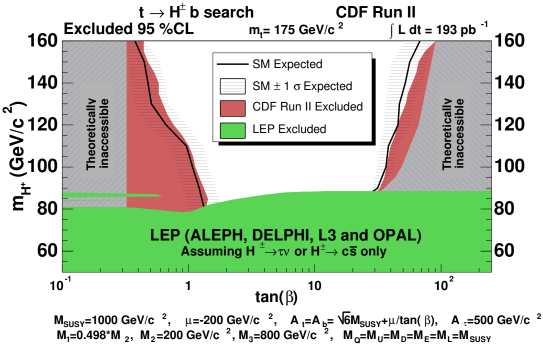
Limits on the mass

LEP $m_{H^\pm} \gtrsim 80$ GeV, model independent

Tevatron For $m_{H^\pm} < m_t$, slight model dependence

- Small and large $\tan\beta$
- Large BR$(t \to H^\pm b)$

B-factories Very model dependent



$m_h^{\max}$ scenario
maximize m_h

Spin Correlations

Modern version of EPR experiment

- Singlet ($J = 0$): $t_\downarrow \bar{t}_\uparrow$
- Triplet ($J = 1$): $t_\uparrow \bar{t}_\uparrow$, $t_\downarrow \bar{t}_\uparrow$, $t_\downarrow \bar{t}_\downarrow$

Measuring the spin of one top we know the spin of the other one *if* overall spin is known

Partonic correlation

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

Helicity basis: spin quantized along momentum direction of $t(\bar{t})$ in partonic CMS

- $q\bar{q} \to t\bar{t}$: $\hat{C}_{q\bar{q}}(4m_t^2) = -1/3$
- $gg \to t\bar{t}$: $\hat{C}_{gg}(4m_t^2) = 1$

In the relativistic limit, $\hat{C}_{ij} \to -1$ for both subprocesses.

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Total correlation

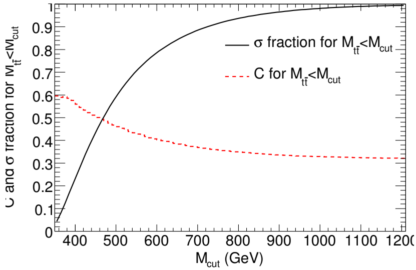
Integrating over $\hat{s}$ and weighting with pdf's gives

$$\mathcal{C}(s) = \sum_{i,j=\{q,\bar{q},g\}} \int \mathrm{d}x_1 \mathrm{d}x_2 \hat{C}_{ij}(x_1 x_2 s) f_i(x_1, \mu_\mathrm{F}^2) f_j(x_2, \mu_\mathrm{F}^2).$$

LHC (gg dominated):

$\mathcal{C} = 0.326$ @NLO (0.319 @LO)

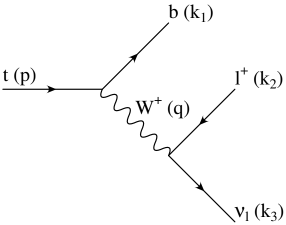
Applying an upper cut on $\hat{s}$ could be benifitial

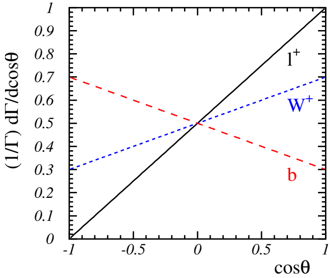


Tevatron ($q\bar{q}$ dominated): $\mathcal{C} = -0.352$ @NLO

Measuring the top quark spin

Rest frame of t with z-axis along spin:
look at angular distribution of decay products
Ex. $t \longrightarrow b\ell^+\nu_\ell$





$$\frac{1}{\Gamma}\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta_i} = \frac{1+\alpha_i\cos\theta_i}{2} \quad , \quad i = b, \ell^+, \nu_\ell, W^+$$

Spin analysing coefficients (power) α_i in SM

$\alpha_b = -\frac{m_t^2 - 2m_W^2}{m_t^2 + 2m_W^2} \approx -0.4$, $\alpha_{\ell^+} = 1$, $\alpha_{\nu_\ell} \approx -0.35$,
$\alpha_{W^+} = -\alpha_b \approx 0.4$

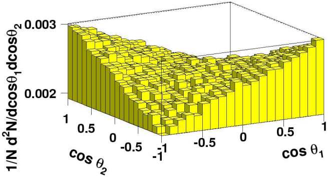
The Correlation in SM

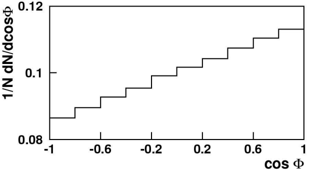
Measure θ_i and θ_j in *respective* rest frame

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

(no linear terms due to parity invariance)

Example: dileptonic channel, $t \to b\ell^+\nu_\ell$ and $\bar{t} \to \bar{b}\ell^-\bar{\nu}_\ell$





project onto one-dim distribution $\Phi = \theta_i - \theta_j$

$$\frac{\mathrm{d}n}{\mathrm{d}\cos(\Phi)} = \frac{1}{2}\Big(1 + \mathcal{D}\alpha_i\alpha_j \cos\Phi\Big)$$

where $\mathcal{D} = -0.24$ @NLO (-0.22 @LO)

Experimental prospects @ LHC

Dileptonic channel, $t \longrightarrow b\ell^+\nu_\ell$ and $\bar{t} \longrightarrow \bar{b}\ell^-\bar{\nu}_\ell$

Possible to reconstruct the neutrino four momenta from

- missing $\vec{p}_\perp$
- assuming t, $\bar{t}$, W^+, W^-, ν_ℓ, and $\bar{\nu}_\ell$ on-shell

Find solution numerically (vary measured energies and momenta within detector resolution if necessary)

Projected accuracy

ATLAS study by F. Hubaut et al, hep-ex/0508061, including systematics etc

- $\mathcal{C}$ with ~ 6 % accuracy
- $\mathcal{D}$ with ~ 3 % accuracy

Systematics limited already with 10 fb^{-1} (remember $\sigma_{t\bar{t}} \simeq 900pb$)

High precision $\Rightarrow$ possible to look for new physics!

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Origin of analysing power α_i

SM: α_i follows from the V-A coupling of W to fermions,

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

- modification to this vertex (right-handed vector or tensor couplings)
- addition of other bosons (scalars or pseudoscalars)

will change the α_i

Top decays into charged Higgs

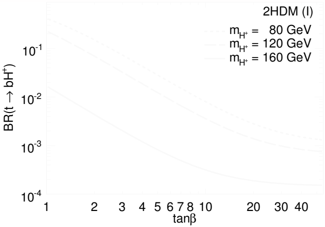
General form of the charged Higgs coupling:

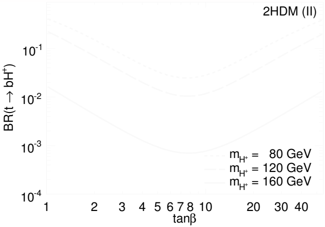
$$\mathcal{L}_{H^+tb} = \frac{g_W}{2\sqrt{2}m_W} V_{tb} H^+ \bar{t} \left[A\,(1-\gamma_5) + B\,(1+\gamma_5) \right] b + h.c.$$

mixture of scalar and pseudoscalar couplings

In the type II (I) 2HDM the tree-level coefficients are
$A = m_t \cot\beta$ and $B = m_b \tan\beta$ ($B = m_b \cot\beta$)
for the leptons the corresponding numbers are
$A = 0$ and $B = m_\tau \tan\beta$ ($B = -m_\tau \cot\beta$)

The branching fractions $t \to bH^+$





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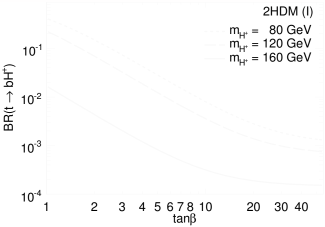

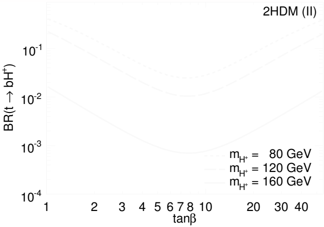

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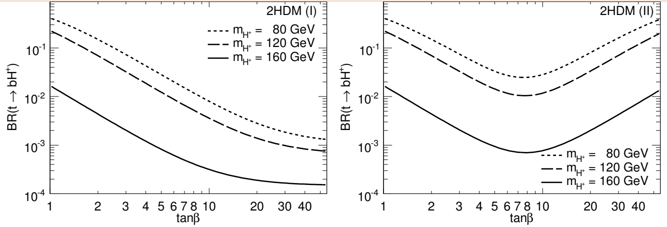

Analysing power @ LO

Narrow width approximation

$$|\mathcal{M}(2 \to 6)|^2 = R_{\lambda\lambda'\kappa\kappa'}(2 \to t\bar{t}) \otimes \rho^i_{\lambda\lambda'}(t \to 3) \otimes \rho^j_{\kappa\kappa'}(\bar{t} \to 3)$$

- R is the helicity-dependent spin density matrix for $t\bar{t}$ production
- $\rho(\bar{\rho})$ are decay density matrices of $t(\bar{t})$,
- i (j) label the available decay channels of $t(\bar{t})$, and
- λ, λ' (κ, κ') are helicity indices for the $t(\bar{t})$

Spin analysing power

obtained by integrating

$$\rho^H_{\lambda\lambda'} = |\mathcal{M}_{\lambda\lambda'}(t \to bH^+ \to bl^+\nu_l)|^2$$

over the appropriate phase space

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Results

Analyzer	Channel: W $(\omega = m_W^2/m_t^2)$	Channel: H $(\xi = m_{H^\pm}^2/m_t^2)$
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	$\frac{1-\xi^2+2\xi\ln\xi}{(1-\xi)^2} \frac{A^2-B^2}{A^2+B^2} f(\xi, A, B)$
ν_l (u)	$\frac{(1-\omega)(1-11\omega-2\omega^2)-12\omega^2\ln\omega}{(1-\omega)^2(1+2\omega)}$	$-\frac{1-\xi^2+2\xi\ln\xi}{(1-\xi)^2} \frac{A^2-B^2}{A^2+B^2} f(\xi, A, B)$

- For SM decays, l^+ is the most efficient analyzer. For Higgs decays it is instead the b-quark or H^+ itself
- Charged Higgs results depend strongly on A^2 and B^2, i.e. on the Lorentz structure of the coupling
- $f(\xi, A, B) \simeq 1$ except when $m_{H^\pm} \to m_t$

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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	$\frac{1-\xi^2+2\xi\ln\xi}{(1-\xi)^2}\frac{A^2-B^2}{A^2+B^2} f(\xi, A, B)$
$\nu_l\ (u)$	$\frac{(1-\omega)(1-11\omega-2\omega^2)-12\omega^2\ln\omega}{(1-\omega)^2(1+2\omega)}$	$-\frac{1-\xi^2+2\xi\ln\xi}{(1-\xi)^2}\frac{A^2-B^2}{A^2+B^2} f(\xi, A, B)$

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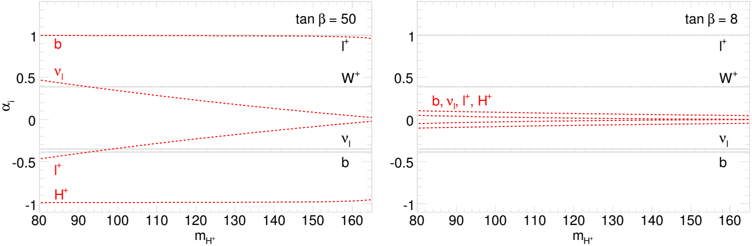
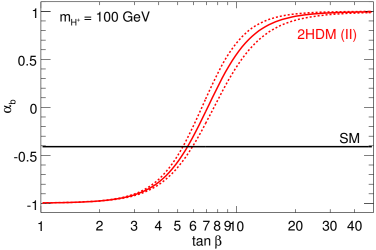
Results in type II 2HDM

$m_{H^\pm}$ dependence for $\tan\beta = 50$ and $\tan\beta = 8$:



$\tan\beta$ dependence of α_b for $m_{H^\pm} = 100$:



Large differences from SM at high (or low) $\tan\beta$. Also true for α_l.

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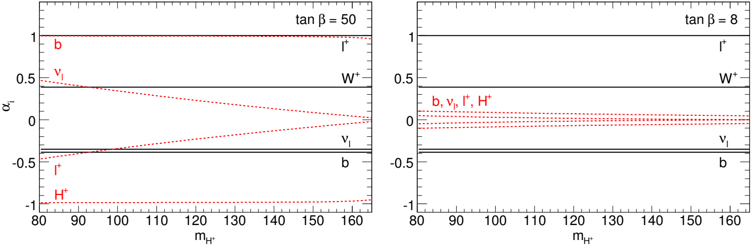

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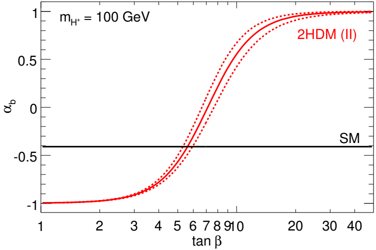

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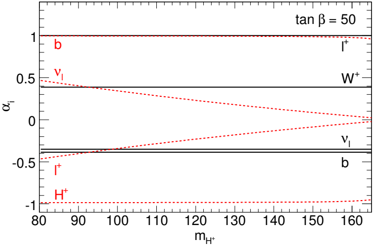

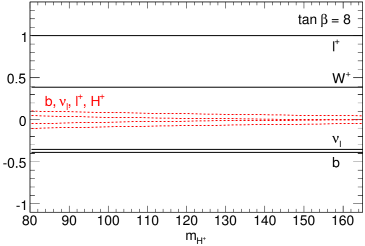

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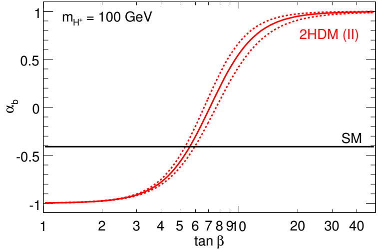

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Higher order (SUSY) QCD corrections

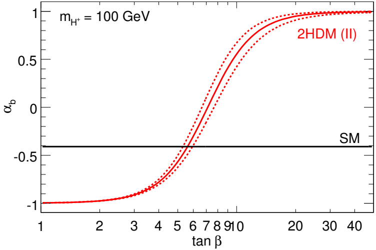
ϵ_b correction

- $y_b = \frac{m_b}{v(1+\epsilon_b \tan\beta)}$ (from gluino-sbottom and chargino-stop loops)
- At one-loop with sparticle masses $\sim M_{\rm SUSY}$:
  $\epsilon_b \simeq \frac{\alpha_s(Q=M_{\rm SUSY})}{3\pi}\frac{\mu}{|\mu|} \sim \pm 10^{-2}$

ϵ_t' correction

$y_t = \frac{m_t(1-\epsilon_t' \tan\beta)}{v}$, numerically similar to ϵ_b

Typically large effect but cancels for α_i, e.g. $\epsilon_b = -\epsilon_t' = \pm 0.01$

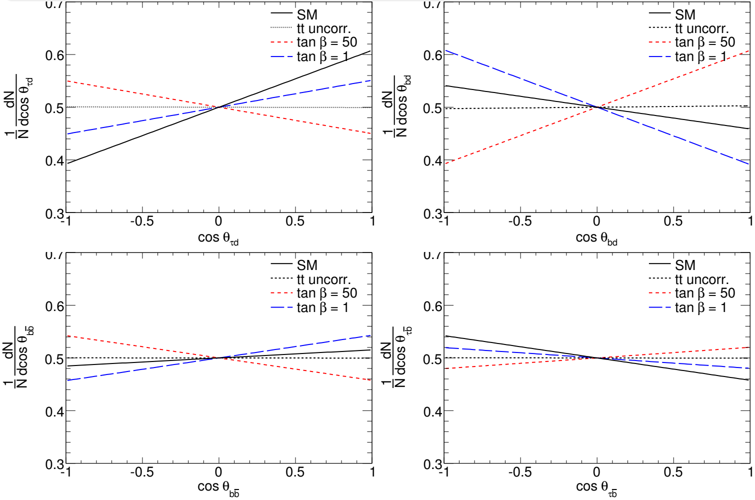


Similar effect from NLO QCD corrections

Resulting correlations: ME level

Consider $t \to bW^+/H^+ \to b\tau^+\nu_\tau$, $\bar{t} \to \bar{b}W^- \to \bar{b}d\bar{u}$:

- SM: with correlations (solid) and without (dotted)
- 2HDM: $m_{H^\pm} = 80$ GeV, $\tan\beta = 50$ and $\tan\beta = 1$



Resulting correlations: getting to the hadron level

Problems

- $H^{\pm}$ couples almost exclusively to $\tau^{\pm}$
  $\Rightarrow$ almost no effect on $\ell^{+}\ell^{-}$ correlation
- additional neutrino from τ decay
  $\Rightarrow$ not possible to find rest frame of t (or $\bar{t}$)

Solution

- resort to hadronic W and τ decay
- measure *azimuthal* angle in respective *transverse* restframe

In analogy with correlation of angles in restframes we expect

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

Numerically we find $\mathcal{D}' \simeq 0.95\mathcal{D}$

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Parton level $\Delta\phi_i$ correlations

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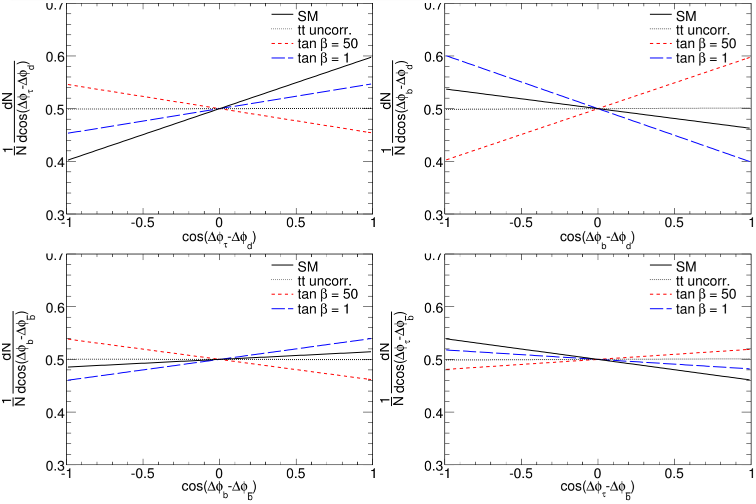

Resulting correlations: hadron level

Simulation

- ME from MadEvent
- Parton showering, hadronization and underlying event from Pythia

Reconstruction

- $|\eta| < 5$
- $k_\perp$ jet clustering in exclusive mode, $d_{ij} = \min(k_{\perp i}^2, k_{\perp j}^2)\Delta R_{ij}^2/R^2$, with $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ and $R^2 = 1$, $d_{cut} = 400$ GeV^2
- simple b and τ jet tagging: $\Delta R(jet, parton) < 0.4$, $|\eta| < 2.5$
- W and t candidates: $|m_{jj} - m_W| < 10 GeV$ and $|m_{bjj} - m_t| < 15 GeV$

Resulting correlations: hadron level

Simulation

- ME from MadEvent
- Parton showering, hadronization and underlying event from Pythia

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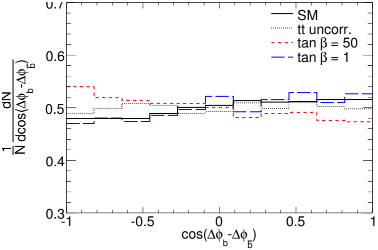
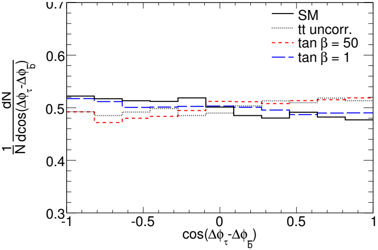
Final results

- for simplicity no mixing of events
- low purity in identifying d jets
  $\Rightarrow$ consider only $\Delta\phi_b - \Delta\phi_{\bar{b}}$ and $\Delta\phi_\tau - \Delta\phi_{\bar{b}}$





- small hadronisation corrections
- need more statistics (fig corresponds to ~ 10 fb^{-}1)

Summary and Outlook

Large $t\bar{t}$ cross-section

- precision studies of top quark properties possible
- possible to search for new physics effects

Charged Higgs bosons

- sure sign of new physics
- LEP-limit $m_{H^\pm} \gtrsim 80$ GeV

Effects on spin correlation

- (pseudo)scalar coupling modifies spin correlation of $t\bar{t}$ pair
- additional neutrinos makes reconstruction difficult
- still some effect in $\tau^+\bar{b}$ and $b\bar{b}$ correlation

Future improvements

- consider complete event simulation
- look at effects in $\ell^+\ell^-$ correlation from leptonic tau-decays

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