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Top quark spin correlations and charged Higgs bosons

Oscar Stål
Uppsala universitet

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work done with D. Eriksson, G. Ingelman, J. Rathsman
JHEP 0801:024,2008, arXiv:0710.5906 [hep-ph]

Top quark spin correlations

- At hadron colliders, pair-produced top quarks come in two spin configurations

  Singlet: $t_{\uparrow}\bar{t}_{\downarrow}$ S=0

  Triplet: $t_{\uparrow}\bar{t}_{\uparrow}, t_{\uparrow}\bar{t}_{\downarrow}, t_{\downarrow}\bar{t}_{\downarrow}$ S=1

- Unlike lighter quarks, t decays before hadronization
  => Information on top spin preserved

- Measuring the spin projection of one top, the spin of the other top can be (statistically) determined *if* the overall spin is known.

=> Modern day EPR experiment

Spin correlations cont'd

1. Select spin quantization axes

   Helicity basis → Spin quantized along momentum directions of $t(\bar{t})$ in $t\bar{t}$ CM frame

2. Determine parton level correlation as fcn. of inv. mass:

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

3. Fold with pdfs and integrate to determine total correlation:

   NLO calculation [Bernreuter et al, Nucl.Phys. B690 (2004) 81-137]

$m_t = 175$

   Tevatron (qq dominated): $\mathcal{C} = -0.352$

   LHC (gg dominated): $\mathcal{C} = 0.326$ (0.319 @ LO)

   Untested prediction of the Standard Model!

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Measuring the top quark spin

- Assume a fully polarized top in its rest frame with spin along z-axis. Weak decay encodes spin in distribution of decay products.

$$\frac{1}{\Gamma}\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta_i} = \frac{1+\alpha_i\cos\theta_i}{2} \qquad i = \{b, l^+, \nu_l, W^+\}$$

Spin analyzing coefficients α_i

$m_t = 175$

Analyzing particle	Decay W^+ $(\omega = m_W^2/m_t^2)$	
b	$-\frac{1-2\omega}{1+2\omega}$	≈ -0.4
W^+/H^+	$\frac{1-2\omega}{1+2\omega}$	≈ 0.4
l^+ $(\bar{d})$	1	1
ν_l (u)	$\frac{(1-\omega)(1-11\omega-2\omega^2)-12\omega^2\ln\omega}{(1-\omega)^2(1+2\omega)}$	≈ -0.35

Best choice →

Measurement of spin correlations

- Exploiting the correlation:

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

Doubly differential distribution with i,j from different tops.
Angles determined in respective rest frames.

$$\mathcal{C}(\hat{\mathbf{a}},\hat{\mathbf{b}})=4\left\langle(\mathbf{S_t}\cdot\hat{\mathbf{a}})(\mathbf{S_{\bar{t}}}\cdot\hat{\mathbf{b}})\right\rangle$$

- Alternatively use “opening angle”
and form the distribution in $\cos\theta_{ij}=\hat{p}_i\cdot\hat{p}_j$

$$\frac{1}{N}\frac{\mathrm{d}N}{\mathrm{d}\cos\theta_{ij}}=\frac{1}{2}\left(1+\mathcal{D}\alpha_i\alpha_j\cos\theta_{ij}\right)$$

where $\mathcal{D}=4\left\langle\mathbf{S_t}\cdot\mathbf{S_{\bar{t}}}\right\rangle=-0.24$ @ NLO [Nucl.Phys. B690 (2004) 81-137]
Less sensitive to acceptance loss by phase-space cuts

D = (-0.217 @ LO)

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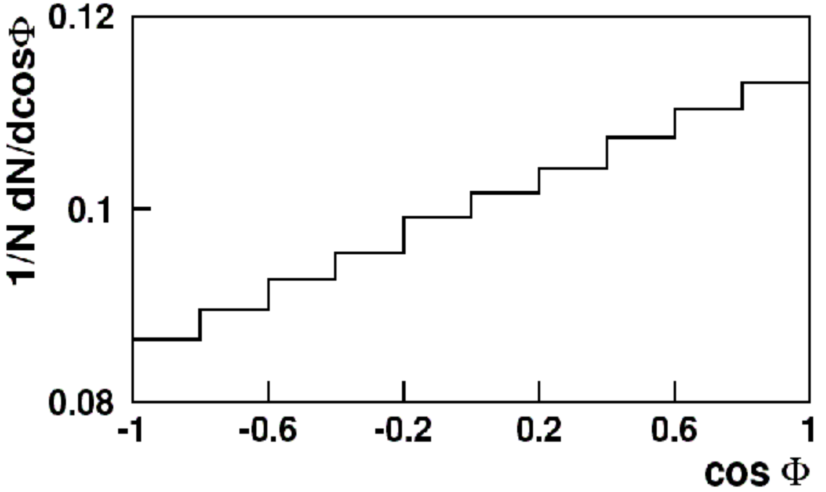
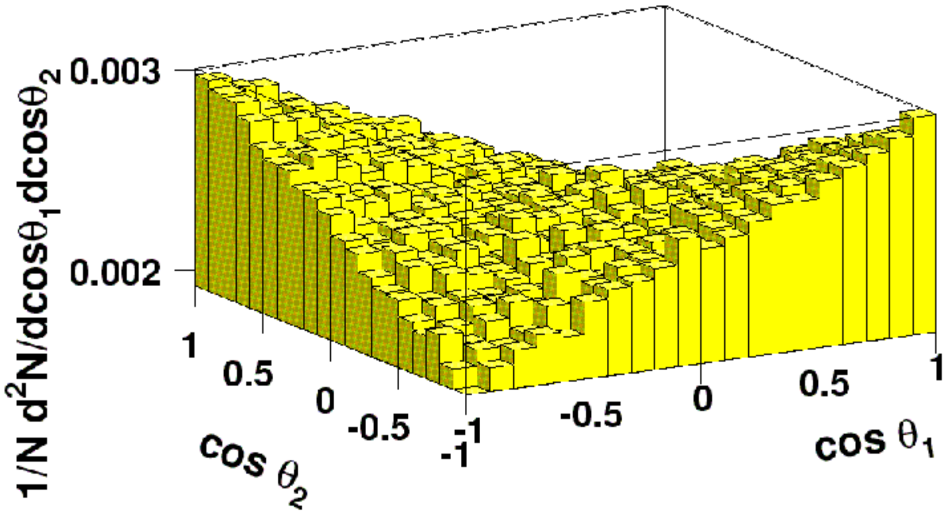
Example: SM dilepton distributions

- Assuming top decay kinematics according to SM
=> reconstruct tt rest frame in the dilepton channel.

$$pp \to t\bar{t} \to bW^+\bar{b}W^- \to b\bar{b}l^+l^-\nu_l\bar{\nu}_l$$





- Experimentally: ATLAS study [F. Hubaut et al, hep-ex/0508061]

$$\Delta\mathcal{C}/\mathcal{C} \sim 6\% \quad \Delta\mathcal{D}/\mathcal{D} \sim 4\%$$

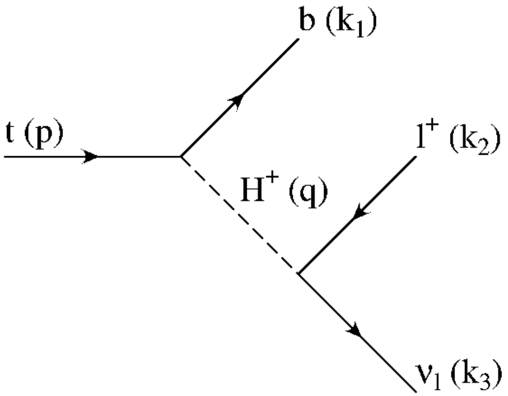
Systematics limited already with 10 fb^{-1}

- High sensitivity → Possible to look for *new physics*

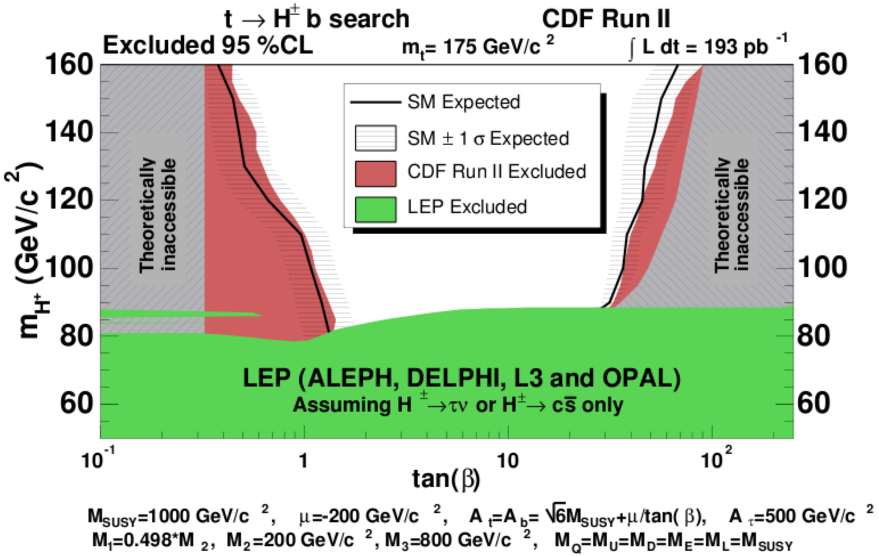
Two-Higgs doublet models (2HDM)

- In the SM with one Higgs doublet, both charged dof. spent on W masses. => Only one neutral h left
- Adding another SU(2)$_L$ Higgs doublet => h, H, A, H$^+$, H$^-$
- Light H$^+$ mediates top decay
- Absolute mass constraint from LEP:

$$m_{H+} > m_W$$



- More stringent limits from Tevatron and B-fact. with some (a great deal of) model dependence
- Indirect constraints: See talk by David Eriksson



Charged Higgs coupling structure

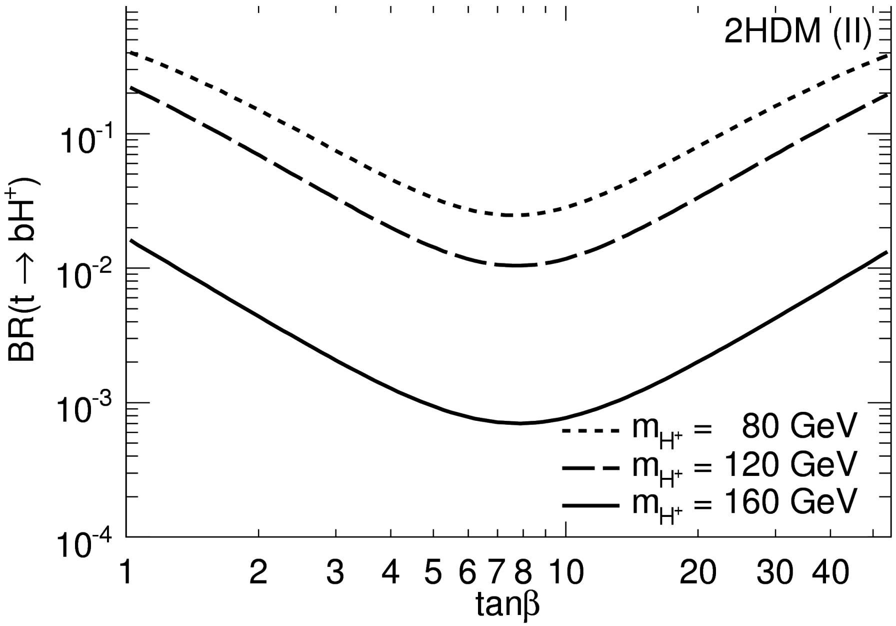
- Charged Higgs-fermion part of 2HDM Lagrangian:

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

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

In MSSM

Coupling	2HDM (I)	2HDM (II)
A	$m_u \cot\beta$	$m_u \cot\beta$
B	$-m_d \cot\beta$	$m_d \tan\beta$
C	$m_l \cot\beta$	$m_l \tan\beta$



Real couplings in CP-conserving 2HDM

Large BR possible for large (small) $\tan\beta$ values

Spin analyzing coefficients for $t \to bH^+ \to b\tau^+\nu_\tau$

- From decay density matrix we determine spin analyzing coefficients for the decay (after phase-space int.)

Analyzing particle	Decay channel $W^+ \ (\omega = m_W^2/m_t^2)$	 $H^+ \ (\xi = m_{H^+}^2/m_t^2)$
b	$-\dfrac{1-2\omega}{1+2\omega}$	$-\dfrac{A^2-B^2}{A^2+B^2} f(\xi, A, B)$
W^+/H^+	$\dfrac{1-2\omega}{1+2\omega}$	$\dfrac{A^2-B^2}{A^2+B^2} f(\xi, A, B)$
$l^+ \ (\bar{d})$	1	$\dfrac{1-\xi^2+2\xi\ln\xi}{(1-\xi)^2}\dfrac{A^2-B^2}{A^2+B^2} f(\xi, A, B)$
$\nu_l \ (u)$	$\dfrac{(1-\omega)(1-11\omega-2\omega^2)-12\omega^2\ln\omega}{(1-\omega)^2(1+2\omega)}$	$-\dfrac{1-\xi^2+2\xi\ln\xi}{(1-\xi)^2}\dfrac{A^2-B^2}{A^2+B^2} f(\xi, A, B)$

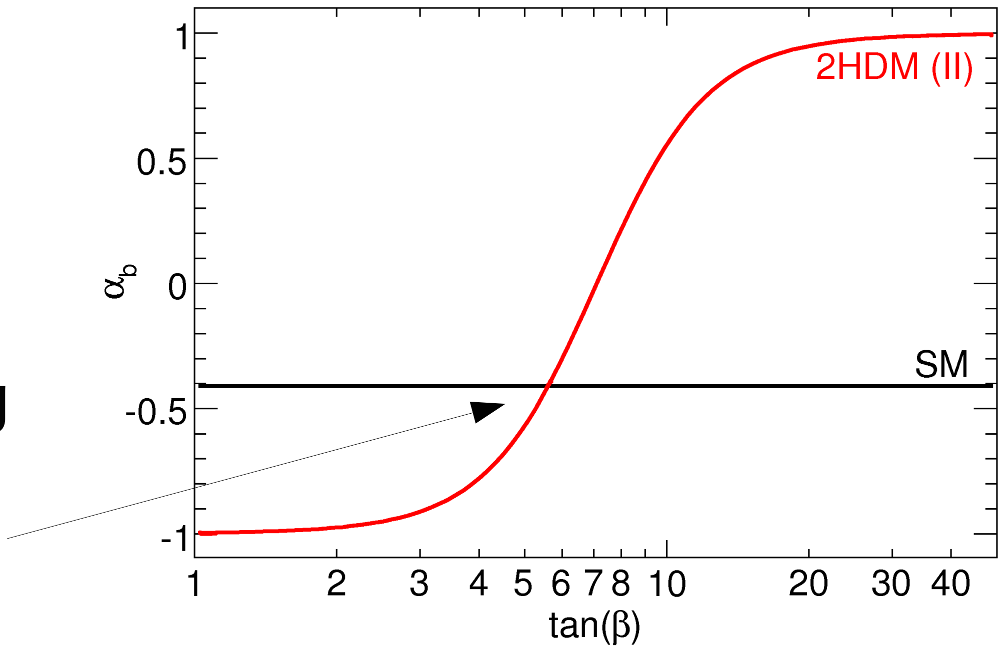
- Charged Higgs coefficients depend on the universal coupling factor

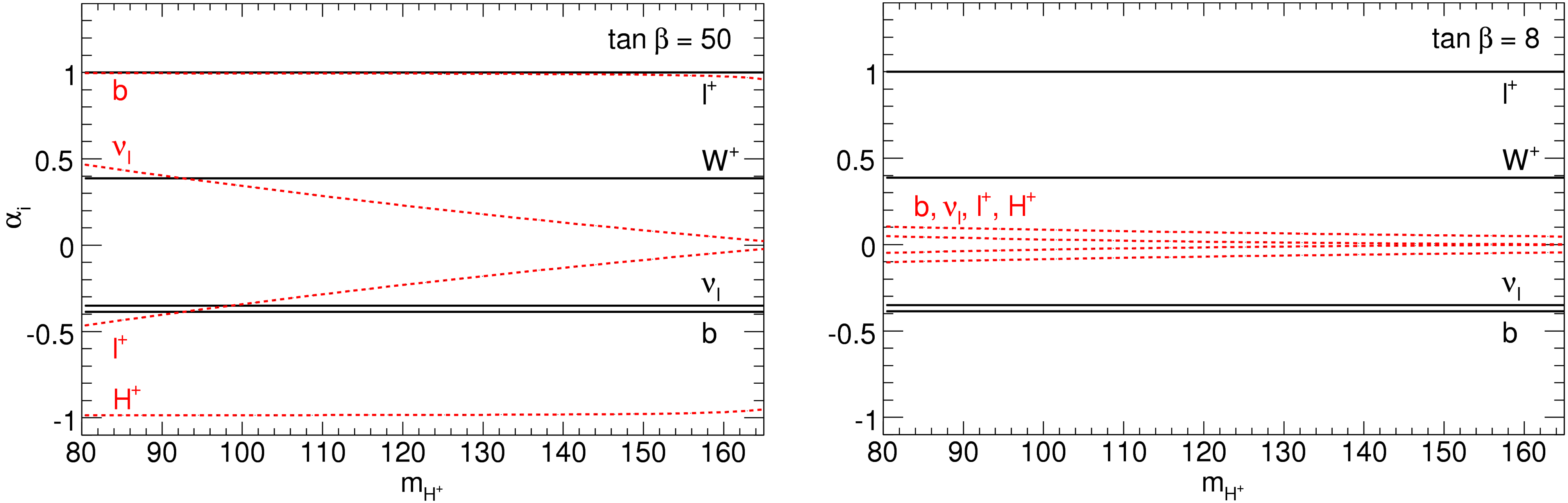
$$\frac{A^2-B^2}{A^2+B^2}$$

- Threshold factor $f(\xi, A, B) \simeq 1$ except for $m_{H^+} \to m_t$

Spin analyzing coefficients in 2HDM (II)

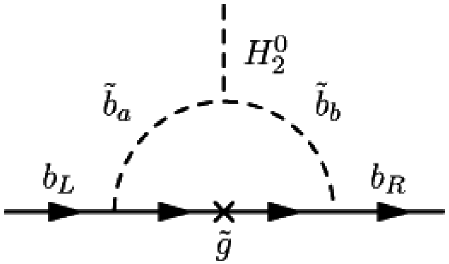
- Large differences from SM for high and low $\tan\beta$
- Could give handle on charged Higgs coupling
- Fake SM at one point



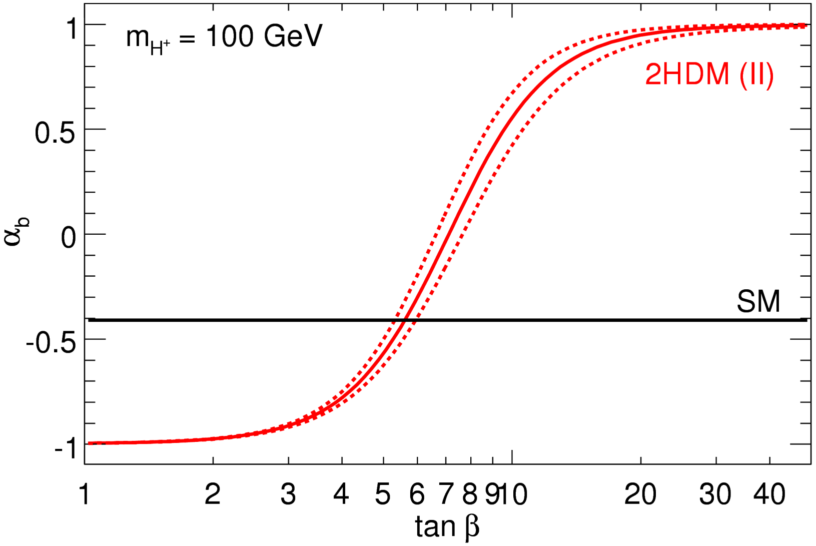


Higher order corrections to SUSY 2HDM

- Yukawa coupling of quarks to “wrong” Higgs doublet induced at 1-loop level
  $\tan\beta$ -enhanced corrections



Coupling	2HDM (I)	2HDM (II)	2HDM ($\overline{\text{II}}$)
A	$m_u \cot\beta$	$m_u \cot\beta$	$m_u \cot\beta\,[1-\epsilon_t' \tan\beta]$
B	$-m_d \cot\beta$	$m_d \tan\beta$	$\frac{m_d \tan\beta}{1+\epsilon_b \tan\beta}$
C	$m_l \cot\beta$	$m_l \tan\beta$	$m_l \tan\beta$



Decoupling limit:

$$\epsilon_b \sim \frac{\mu}{|\mu|}\frac{\alpha_s(M_{\mathrm{SUSY}})}{3\pi} \simeq 10^{-2}$$

$$\epsilon_b = -\epsilon_t' = \pm 0.01$$

- Similar effect from standard NLO QCD corrections [hep-ph/0211098]

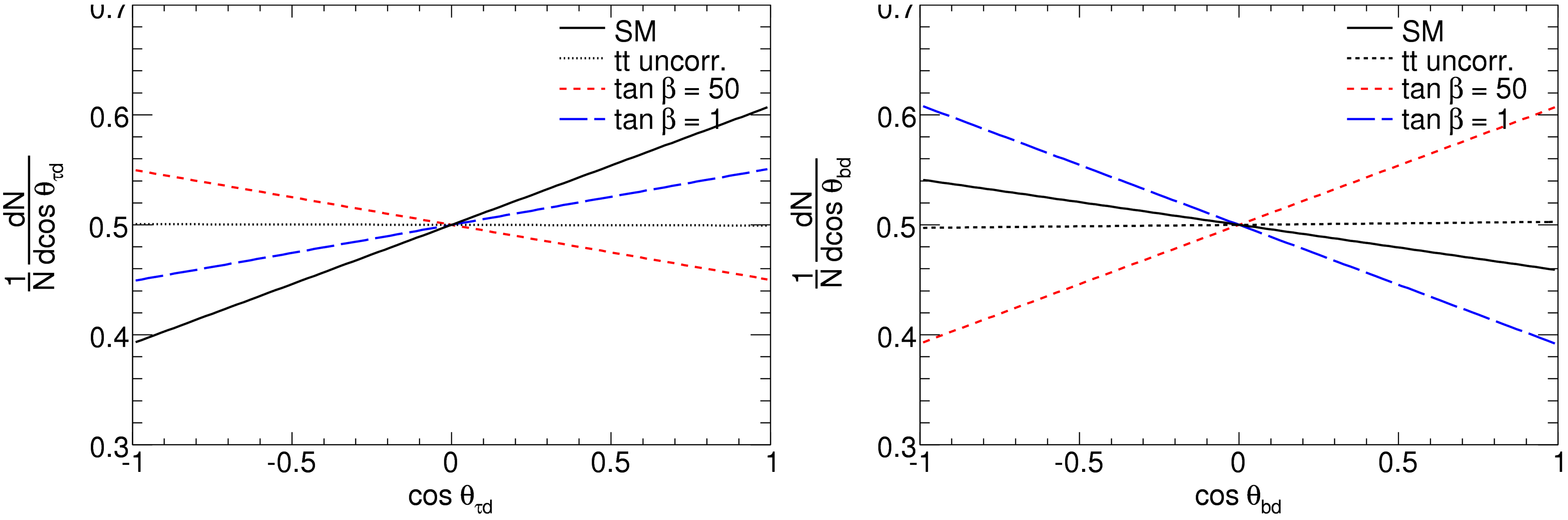
Parton-level correlations in 2HDM (II)

- D-type distributions $$\frac{1}{N}\frac{\mathrm{d}N}{\mathrm{d}\cos\theta_{ij}} = \frac{1}{2}\left(1+\mathcal{D}\alpha_i\alpha_j\cos\theta_{ij}\right)$$

$$t \longrightarrow bH^+ \longrightarrow b\tau^+\nu_\tau$$

$$\bar{t} \longrightarrow \bar{b}W^- \longrightarrow \bar{b}\bar{u}d$$

+ cc.



- Tau assumed stable here, full truth used to reconstruct CM

=> tau-d largest corr. in SM while b-d better for 2HDM

From MC parton “truth” to hadron level

Problem: Charged Higgs decays to τ
- Almost no effect on e or μ correlations
- Additional neutrinos from τ decay
  => Impossible to reconstruct partonic CM frame

Solution:
- Resort to hadronic decays of W and tau
- Reconstruct *transverse* rest frames of top quarks
- Measure azimuthal angles in these frames

In analogy with CM correlations we expect

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

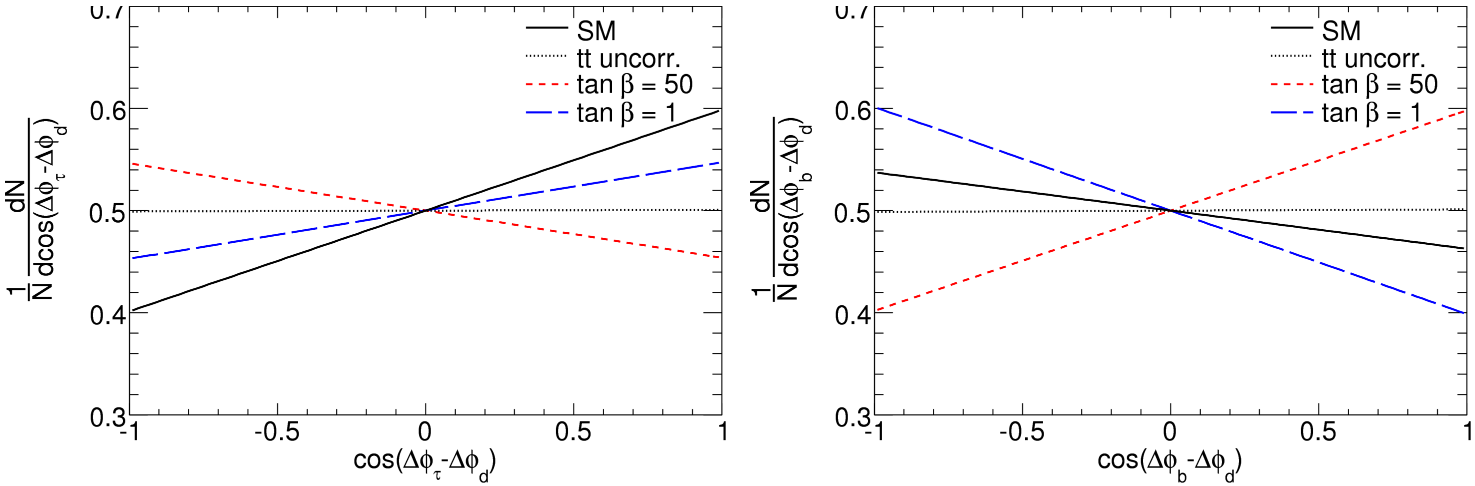
Numerically, we find for the LHC at LO:

$\mathcal{D}'=0.9\mathcal{D}$ (Remember that $\mathcal{D}=-0.217$)

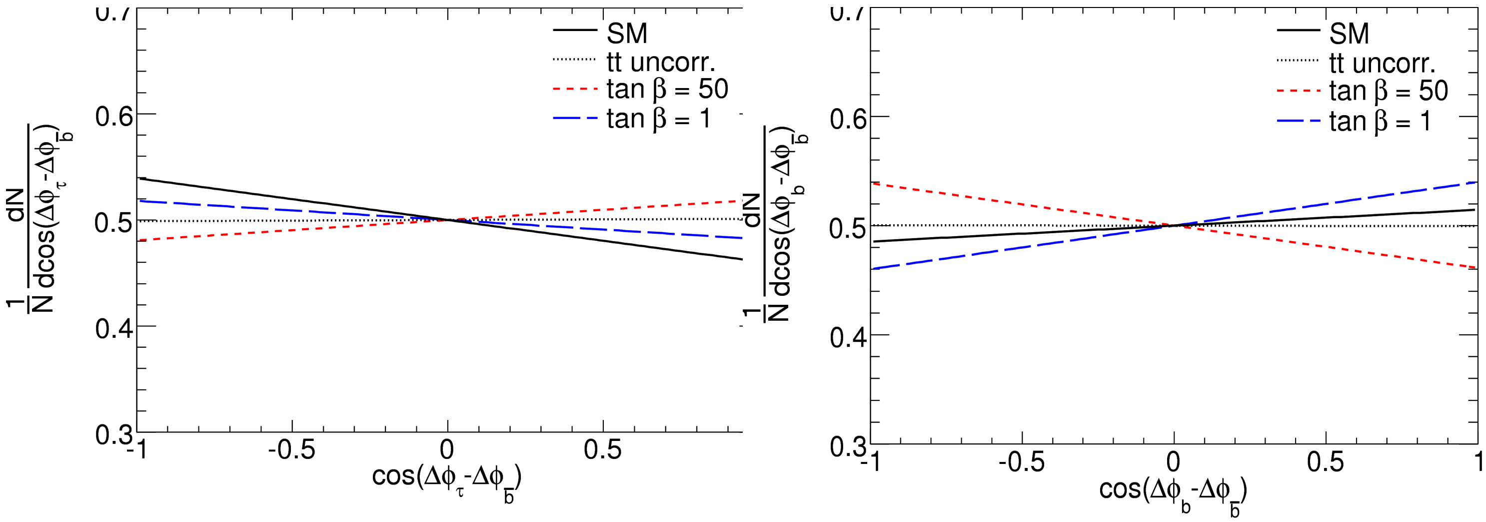
Parton-level results from azimuthal angles

As before: $t \longrightarrow bH^+ \longrightarrow b\tau^+\nu_\tau$

$\bar{t} \longrightarrow \bar{b}W^- \longrightarrow \bar{b}\bar{u}d$ + cc



Without identifying the d-quark:



Hadron-level MC simulation

- Full 2 → 6 ME from MadEvent, cross-check with TopReX
  Parton showering, hadronization, UE with PYTHIA

- Decay channels: $t \longrightarrow bH^+ \longrightarrow b\tau^+\nu_\tau$ $\quad \tau \longrightarrow \mathrm{hadrons}$ with TAUOLA

  $\bar{t} \longrightarrow \bar{b}W^- \longrightarrow \bar{b}\bar{u}d$

- Reconstruction:

  $|\eta| < 5$ $\quad k_\perp$ jet finding $d_{\mathrm{cut}} = 20\ \mathrm{GeV}$

  “Flavor tagging”: $\Delta R(\mathrm{jet}, \mathrm{parton}) < 0.4 \quad |\eta| < 2.5$

  W and top candidates from jet combinations

  $|m_{jj} - m_W| < 10\ \mathrm{GeV}$

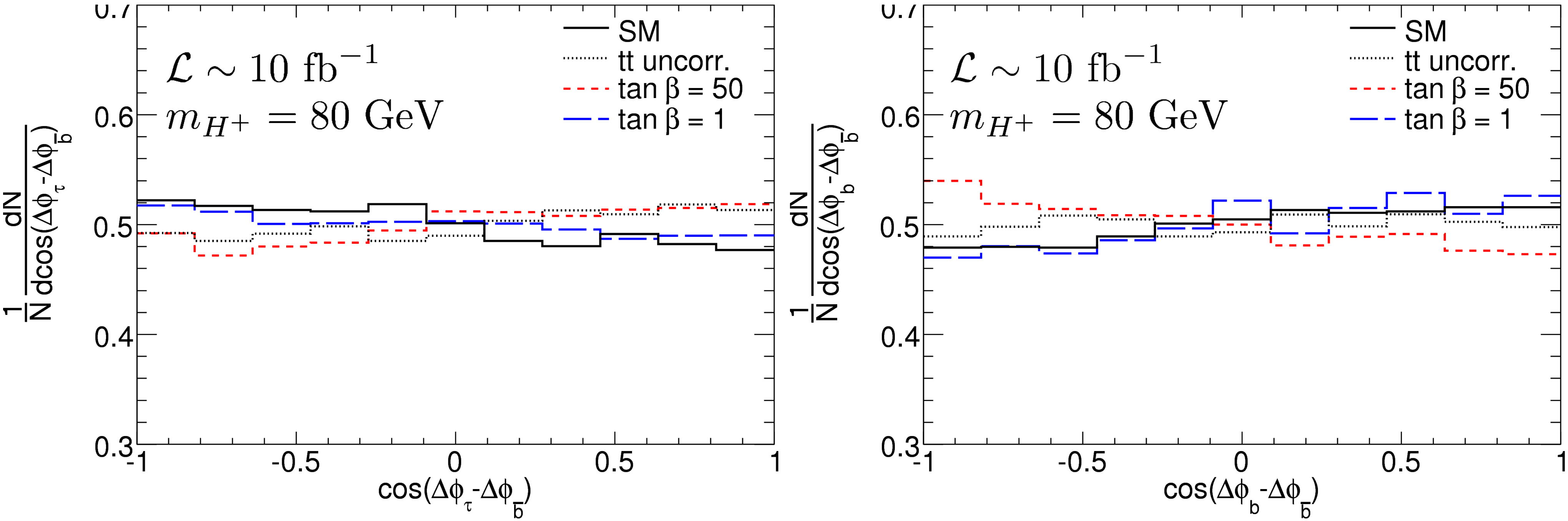
  $|m_{jjb} - m_t| < 15\ \mathrm{GeV}$

  Analyzed events selected on basis of correct topology

- No backgrounds or detector effects at this point

Hadron level results

- From SM side of the event we use b quark as spin analyzer
- On H^+ side we can use either tau- or b-jet



- Hadron level results similar to parton level (normalized dist)
- bb distribution most sensitive to new physics
  Hard enough b quark required => $m_{H+} \lesssim 130$ GeV

Summary and Conclusions

- Top quark spin correlations are predicted by SM
Testable at the LHC

- Large statistics allows for new physics searches in tt

- H^+ in top decays can influence angular distributions of decay products

- Spin analyzing coefficients shown for 2HDM.
SM: lepton most efficient analyzer; 2HDM: b-quark (or H^+)

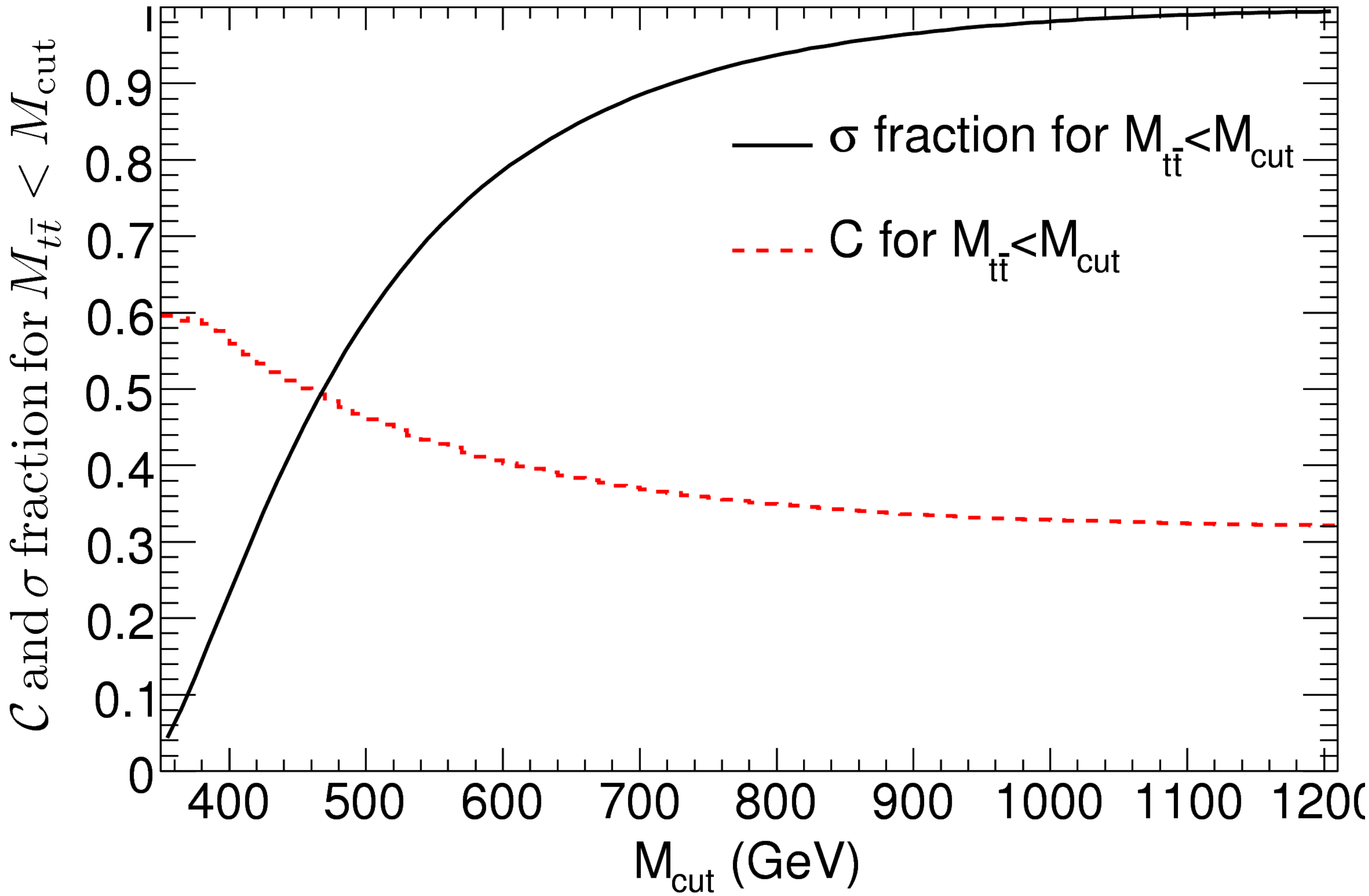
- $H^+ \rightarrow \tau^+ \nu_\tau$ decay prevents reconstruction of rest frames.
Azimuthal distributions in transverse rest frames

- Hadron-level MC simulations indicate small H^+ effect.
Highest sensitivity to interesting case with large $\tan\beta$

EXTRAS

Increasing degree of correlation

- Applying an upper cut on invariant mass improves the degree of correlation at the LHC



- Remember high statistics at 14 TeV: $\sigma(pp \to t\bar{t}) \simeq 900 \text{ pb}$