Probing Two Higgs doublet models using top-quark observables

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in collaboration with
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(arXiv:1307.1158)

13th August, 2013

PLAN

- **Introduction**

  ⇒ **The Top quark**
  ⇒ **Top-quark properties**
  ⇒ **Top-decay distribution**
  ⇒ **Top Polarization**

- **Two Higgs Doublet Models.**

- **top-charged Higgs associated production in 2HDM at LHC.**

- **Conclusions**

Top Quark Properties

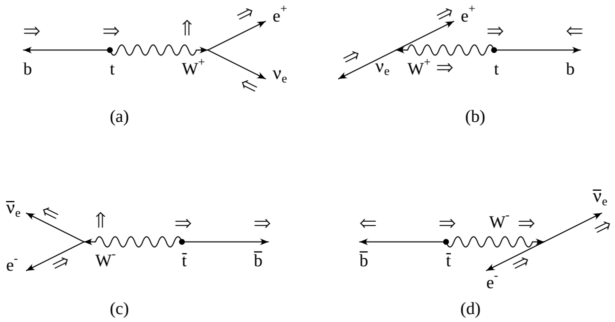
	Measurement	SM prediction
Mass	(173.2 ± 0.9) GeV[1]	-
Charge	Not 4/3(94% CL)[2]	2/3
Spin	-	1/2

$\Rightarrow$Need to know Top-quark properties precisely.

- the heaviest fundamental particle discovered so far
- Because of its large mass, its decay width is very large
- Its life time is $\sim 5 \times 10^{-25}$s which is smaller than hadronization scale $\sim 3 \times 10^{-24}$s
- Thus polarization of a bare top quark is a measurable quantity.

[1]FERMILAB-TM-2504-E, arXiv:1107.5255
[2]DØ Note 4876-CONF

Correlation between ℓ^+ and top spin



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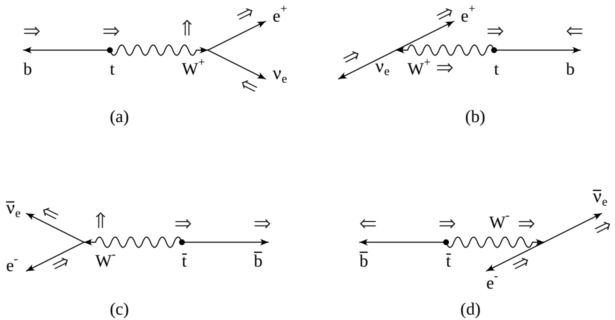

Top Polarization

- In the top-rest frame, the distribution of its decay products is given by

$$\frac{1}{\Gamma}\frac{d\Gamma_f}{d\cos\theta_f} = \frac{1}{2}\left(1 + \kappa P_t \cos\theta_f\right)$$

- P_t is the top-polarization and is defined as

$$P_t = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow},$$

- κ is known as the analysing power
- The ℓ^+ and d quark are the best spin analyzers with $\kappa_{\ell^+} = \kappa_{\bar{d}} = 1$,
- Thus the ℓ^+ or d have the largest probability of being emitted in the direction of the top spin,

Top Polarization Contd

A issue

- These distributions are defined in top-quark rest frame.
- Reconstruction of top-rest frame is difficult at LHC

Our Prescription

- We study lab-frame distributions of top-decay products,
- Decay-lepton angular distribution is insensitive of anomalous tbW couplings at linear order,

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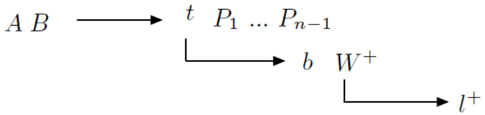
$\Rightarrow$ New Physics

A generic top-production process



Lepton angular distributions are independent of anomalous tbW couplings under following assumptions:

[Godbole, Rindani], [Grzadkowski]

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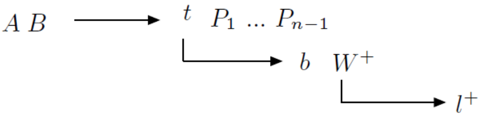

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- top is on-shell; narrow-width approximation for top,

$$|\mathcal{M}|^2 = \frac{\pi\delta(p_t^2 - m_t^2)}{\Gamma_t m_t} \sum_{i,j} \rho(\lambda, \lambda')\Gamma(\lambda, \lambda')$$

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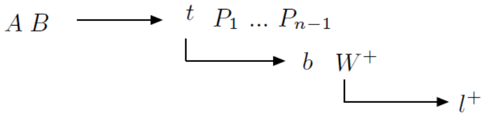

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- couplings f_{1R}, f_{2L} and f_{2R} are small,

Decay distribution

Using NWA for top quark, the decay distribution can be separated into production and decay parts

$$d\sigma = \sum_{\lambda,\lambda'} \left[\frac{(2\pi)^4}{2I} \rho(\lambda,\lambda') \delta^4 \left(k_A + k_B - p_t - \sum_i^{n-1} p_i \right) \frac{d^3 p_t}{2E_t (2\pi)^3} \prod_i^{n-1} \frac{d^3 p_i}{2E_i (2\pi)^3} \right]$$

$$\times \left[\frac{1}{\Gamma_t} \, \frac{(2\pi)^4}{2m_t} \Gamma(\lambda,\lambda') \delta^4 (p_t - p_b - p_\nu - p_\ell) \frac{d^3 p_b}{2E_b (2\pi)^3} \, \frac{d^3 p_\nu}{2E_\nu (2\pi)^3} \frac{d^3 p_\ell}{2E_\ell (2\pi)^3} \right].$$

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Production part $(\phi_t = 0)$

$$\int \frac{d^3 p_t}{2E_t (2\pi)^3} \prod_i^{n-1} \frac{d^3 p_i}{2E_i (2\pi)^3} \frac{(2\pi)^4}{2I} \rho(\lambda,\lambda') \delta^4 \left(k_A + k_B - p_t - \sum_i^{n-1} p_i \right)$$
$$= d\sigma_{2\to n}(\lambda,\lambda') dE_t \, d\cos\theta_t$$

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Decay part (in rest frame of top quark)

$$\frac{1}{\Gamma_t} \frac{(2\pi)^4}{2m_t} \int \frac{d^3 p_b}{2E_b (2\pi)^3} \frac{d^3 p_\nu}{2E_\nu (2\pi)^3} \frac{d^3 p_\ell}{2E_\ell (2\pi)^3} \Gamma(\lambda,\lambda') \delta^4 (p_t - p_b - p_\nu - p_\ell)$$

$$= \frac{1}{32\Gamma_t m_t} \frac{E_\ell}{(2\pi)^4} \frac{\langle \Gamma(\lambda,\lambda') \rangle}{m_t E_\ell} dE_\ell d\Omega_\ell dp_W^2$$

Angular distribution (contd.)

Combining production and decay part, we get

$$d\sigma = \frac{1}{32\Gamma_t m_t (2\pi)^4} \left[\sum_{\lambda,\lambda'} d\sigma_{2\to n}(\lambda,\lambda') \times g^4 A^{cm}(\lambda,\lambda') \right]$$
$$\times \quad dE_t d\cos\theta_t d\cos\theta_\ell d\phi_\ell$$
$$\times \quad E_\ell F(E_\ell) |\Delta(p_W^2)|^2 dE_\ell dp_W^2$$

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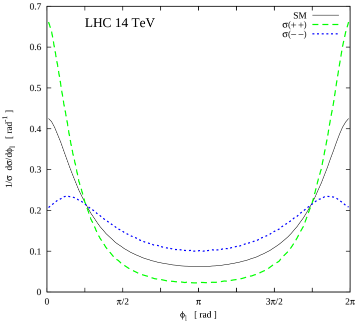
Contributions of anomalous tbW couplings cancels between numerator and denominator,

Thus, angular distribution of decay charged-lepton is independent of any new physics in Wtb coupling in the top decay.

Lepton Azimuthal distribution as top-spin analyzer



- ϕ_ℓ distribution is symmetric around $\phi_\ell = \pi$.
- We define azimuthal asymmetry of charged lepton as :

$$A_\phi = \frac{\sigma(\cos\phi_\ell > 0) - \sigma(\cos\phi_\ell < 0)}{\sigma(\cos\phi_\ell > 0) + \sigma(\cos\phi_\ell < 0)},$$

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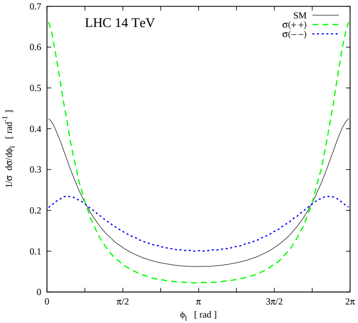

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<u>A_ϕ is also left-right asymmetry</u>

Two Higgs doublet Model

A simple and minimal extension of the SM is to include one more Higgs doublet into the theory. so we have two Higgs doublets with the same quantum numbers

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \phi_1^0 \end{pmatrix} \; ; \; \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix}$$

with hypercharges $Y_1 = Y_2 = 1,$ and two vev's viz., v_1 and v_2 with $\tan\beta = v_2/v_1$.

Higgs spectrum in 2HDM

- Charged Higgs pair, $H^{\pm}$,
- 2 CP even Higgs, H and h,
- 1 CP odd Higgs, A.

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Depending on the Higgs couplings to fermion doublets, there are different types of THDMs.

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Two Higgs Doublet Models (THDMs)

The four possible models Type I, Type II, Type Y (Flipped) and Type X (Lepton-Specific) are

Model	$g_{\bar{u}dH^+}$	$g_{l\bar{\nu}H^+}$
I	$\frac{ig}{\sqrt{2}\,M_W}V_{ud}\left[-m_d\cot\beta P_R + m_u\cot\beta P_L\right]$	$\frac{ig}{\sqrt{2}\,M_W}\left[-m_l\cot\beta P_R\right]$
II	$\frac{ig}{\sqrt{2}\,M_W}V_{ud}\left[m_d\tan\beta P_R + m_u\cot\beta P_L\right]$	$\frac{ig}{\sqrt{2}\,M_W}\left[m_l\tan\beta P_R\right]$
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- type I and X have same coupling to quarks but different coupling to leptons
- Similarly for type II and type Y
- In large $\tan\beta$ region, type I becomes fermiophobic while type X becomes quark-phobic but leptophilic

Constraints on Charged Higgs mass m_{H^+} and $\tan\beta$

From **Physics Report 516 (2012) 1-102**

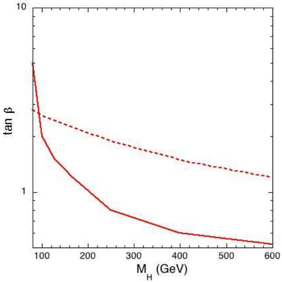
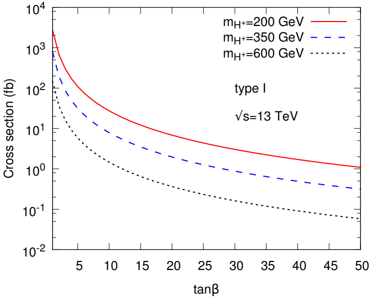


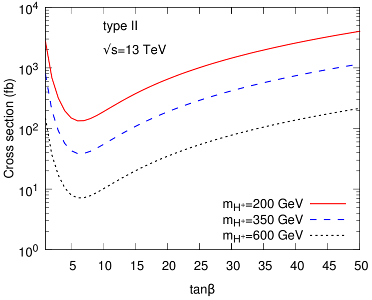
Figure: Bounds on $tan\beta$ in the type I 2HDM as a function of the charged-Higgs mass M_H.

- The solid line is the bound from $Z \to b\bar{b}$ and ΔM_{B_s}.
- The dashed line is the bound which arises from $B \to X_s\gamma$.

Cross section in type I and type II THDMs

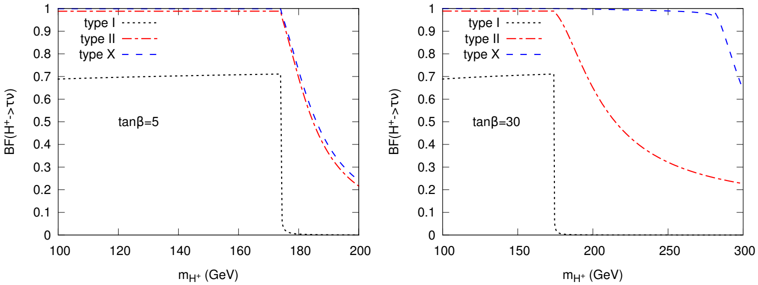
We consider associated production of top with charged Higgs at LHC in the process $pp \to tH^-$.





- In type I THDM
  Cross section, $\sigma \propto (F_1 + F_2)(m_t^2 + m_b^2) \cot^2 \beta$
- In type II THDM
  Cross section, $\sigma \propto (F_1 + F_2)(m_t^2 \cot^2 \beta + m_b^2 \tan^2 \beta)$

Branching fractions of $H^+ \to \tau\nu$ in THDMs



- We consider H^+ decaying to $\tau\nu$ in our analysis.
- BF$(H^+ \to \tau\nu)$ remains 100% till top threshold in type II and X models
- In type I THDM, BF$(H^+ \to \tau\nu)$ competes with $H^+ \to cs$

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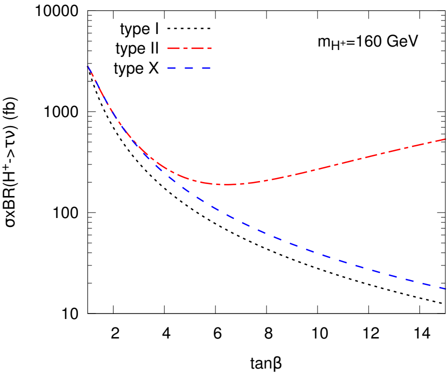
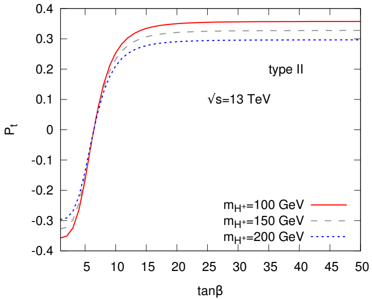
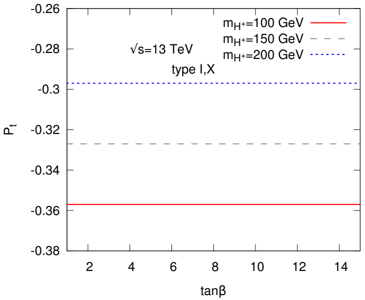
Cross section $\times$ BF in THDMs



- Models I, II and X can be easily distinguished in large β region.
- In low $\tan\beta$ region, rates are almost equal
- No way to distinguish between models

Top polarization as a function of $\tan\beta$





- P_t arises mainly only due to parity violating terms in vertex-: $\Gamma = [m_b \tan\beta P_L + \ m_t \cot\beta P_R]$,

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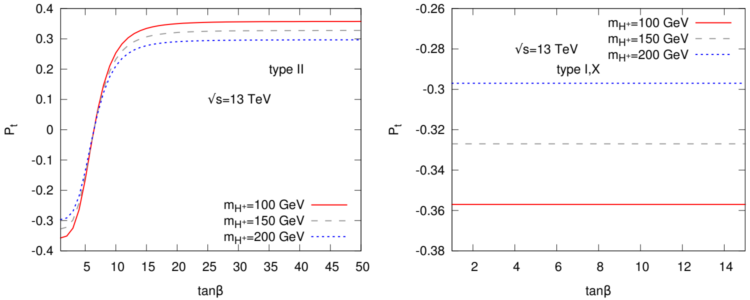

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- In type II THDM, γ_5 term vanishes at $\tan\beta = \sqrt{m_t/m_b}$, at this value of $\tan\beta$, we expect P_t to be zero.

Discriminating type X and type II THDMs with P_t

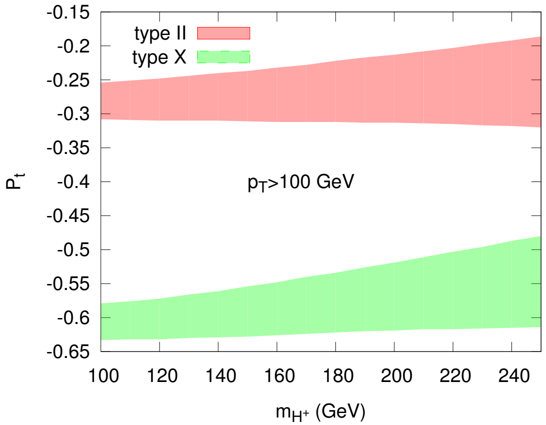


Figure: top polarization as function of the charged Higgs mass for $\sqrt{s} = 13$ TeV and $\tan\beta = 5$ for type X and type II 2HDMs.

Discriminating type X and type II THDMs with A_ϕ

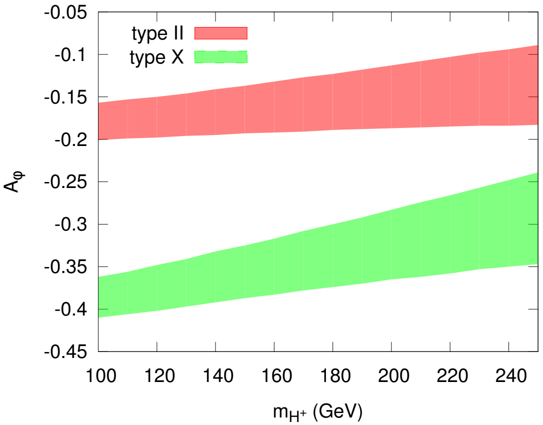
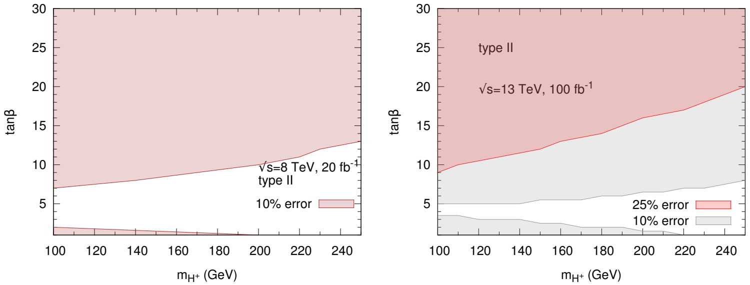


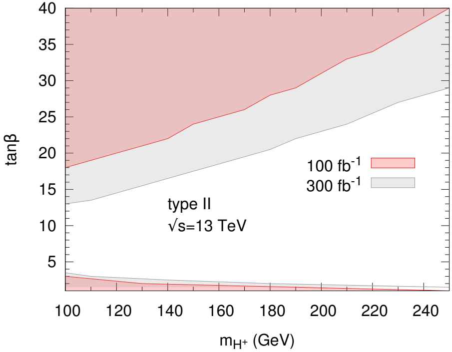
Figure: A_ϕ as function of the charged Higgs mass for $\sqrt{s} = 13$ TeV and $\tan\beta = 5$ for type X and type II 2HDMs.

Exclusion with top polarization



- This exclusion is comparable to exclusion coming from top-pair production

Exclusion with left-right asymmetry A_ϕ



- This asymmetry is defined in the lab frame and thus expected to be measured with high precision.

Sensitivity of Top polarization on $\tan\beta$

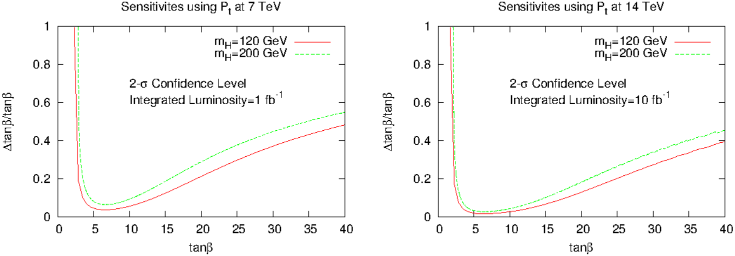


Figure: Sensitivity of P_t on $\tan\beta$ at 7 TeV and 14 TeV

- P_t is the most sensitive for $\tan\beta \sim 3-20$ and $\tan\beta \sim 3-25$ for 7 TeV and 14 TeV LHC respectively.

Sensitivity of A_ϕ on $\tan\beta$

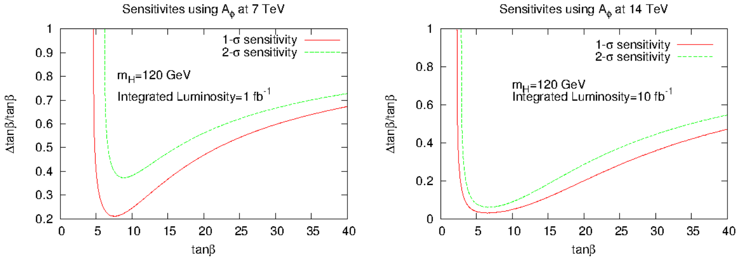


Figure: Sensitivity of A_ϕ on $\tan\beta$ at 7 TeV and 14 TeV

- A_ϕ is the most sensitive for $\tan\beta \sim 5 - 13$ and $\tan\beta \sim 3 - 25$ for 7 TeV and 14 TeV LHC respectively.

Conclusions

- Top quark polarization provides an additional handle to probe new physics scenarios.
- Azimuthal asymmetry of charged lepton is a clean and pure probe of top-polarization.
- Associated-tH^- production is a good process to probe THDMs
- In MSSM/THDMII, top-polarization proves to be sensitive probe of parameter $\tan\beta$,
- P_t and A_ϕ can be good observables to distinguish between type X and type II THDMs.

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(arXiv:1307.1158)

Conclusions

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THANKS

Sensitivity analysis

- We investigate the accuracy to which one can determine $\tan\beta$ from P_t, and A_ϕ,

Accuracy of the determination of parameter $\tan\beta$ at $\tan\beta_0$

is $\Delta\tan\beta$ if $|O(\tan\beta) - O(\tan\beta_0)| < \Delta O(\tan\beta_0)$ for $|\tan\beta_0 - \tan\beta| < \Delta\tan\beta$

- $\Delta O(\tan\beta_0)$ is the statistical fluctuation in O at an integrated luminosity $\mathcal{L}$,

- For P_t and A_ϕ, the statistical fluctuations at a CL f are given by $\Delta O = f/\sqrt{\mathcal{L}\sigma} \times \sqrt{1 - O^2}$, where O denotes P_t or A_ϕ.