Determining parameters of 2HDM in associated production of charged Higgs with top at LHC

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Top quark - A window to new physics

- $\mathbf{m_{top}} \sim 172$ GeV $\sim$ EW scale,
- Decay width $\boldsymbol{\Gamma_{top}} \sim \mathbf{1.5GeV} > \boldsymbol{\Lambda_{QCD}}$ (hadronization scale),
- Hence, it decays before hadronization,
- And, its spin/polarization can be studied through its decay products,
- Decay lepton angular distribution is insensitive to anomalous **tbW** couplings[1],
- Hence, a *clean* and *uncontaminated* probe of new physics in top production.

[1] Godbole,Rindani

Top-polarization

- Can be determined through its decay products,
- In SM, dominant decay is Br($\mathbf{t \longrightarrow bW \sim 0.998}$)

Angular distribution of a decay product f of top in top-rest frame

$$\frac{1}{\Gamma_f}\frac{d\Gamma_f}{d\cos\theta_f} = \frac{1}{2}(1 + \kappa_f P_t \cos\theta_f).$$

θ_f is angle between **f** and top spin,

- $P_t = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$, is top polarization.
- $N_\uparrow$ and $N_\downarrow$ refer to the number of positive and negative helicity tops respectively.
- κ_f is the spin analyzing power of **f**.

Why lepton angular distributions are significant

- Larger κ_f means more sensitive probe of $\mathbf{P_t}$
- At tree level, $\kappa_{\ell^+} = \kappa_{\bar{d}} = 1$, while $\kappa_{\nu_\ell} = \kappa_u = -0.30$ and $\kappa_b = -\kappa_{W^+} = -0.39$,
- At LHC, leptons can be measured with high precision,
- Angular distributions of charged lepton from top decay are independent of anomalous **tbW** couplings involved in top decay,

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Lepton angular distributions

A *clean glass* to look for any new physics in top production.

- Hence, we focus on leptonic decays of the top.

Determination of top-polarization @ LHC

- $\mathbf{P_t}$ can be determined from angular distributions of top-decay products,
- But, this requires reconstruction of the top-rest frame,
- At LHC, this task is extremely difficult if not impossible,
- So, we have to devise a new observable in lab frame of LHC which is a faithful probe of $\mathbf{P_t}$,
- In this work, we study azimuthal distribution of charged lepton in lab frame and using this, construct an asymmetry,
- We find that this asymmetry is a convenient probe of $\mathbf{P_t}$ and the underlying new physics in top production.

Main objectives of this work

- Study top polarization in associated production with charged Higgs in Two Higgs doublet model (2HDM) at the LHC,
- Construct lab frame observables to determine top polarization,
- Then to determine the sensitivity of these observables to the measurement of model parameters.

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

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

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

Higgs spectrum in **2HDM**

- Charged Higgs pair, $\mathbf{H^{\pm}}$,
- 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 **4** types of **2HDMs**.

- We study the process $\mathbf{pp \longrightarrow tH^-}$ at LHC, which proceeds through $\mathbf{gb \longrightarrow tH^-}$ with $\mathbf{tbH^-}$ vertex in **2HDM**,

Figure: Born diagrams: s-channel bottom exchange and u-channel top exchange.

- Various studies have shown the discovery potential of charged Higgs in this channel,

- Once the charged Higgs will be discovered, the next important task would be to determine model parameters $\mathbf{m_H}$ and $\mathbf{\tan\beta}$,

Structure of $\mathbf{tbH^-}$ vertex in 2HDMII

- Structure of $\mathbf{tbH^-}$ interaction vertex :

$$\Gamma = \frac{g}{2\sqrt{2}M_W}\left[m_b \tan\beta(1-\gamma_5) + m_t \cot\beta(1+\gamma_5)\right]$$

- $\mathbf{P_t}$ arises mainly only due to parity violating terms viz. γ_5 in the vertex,

- We expect high degree of top polarization due to the chiral nature of the interaction Lagrangian,

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

Procedure

- We use narrow width approximation to separate the production and decay parts :

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

- $\rho(\lambda,\lambda')$ and $\Gamma(\lambda,\lambda')$ are the 2×2 top production and decay spin density matrices and $\lambda, \lambda' = \pm 1$ denote the sign of the top helicity,
- Using the NWA the differential cross section for top production and decay, with inclusive decay of H^- can be written as

$$\begin{aligned} d\sigma &= \frac{1}{32\,\Gamma_t m_t}\frac{1}{(2\pi)^4}\left[\sum_{\lambda,\lambda'} d\sigma(\lambda,\lambda') \times \left(\frac{\Gamma(\lambda,\lambda')}{p_t \cdot p_\ell}\right)\right] \\ &\times\ E_\ell\, |\Delta(p_W^2)|^2\, d\cos\theta_t\, d\cos\theta_\ell\, d\phi_\ell dE_\ell\, dp_W^2, \end{aligned}$$

Spin density matrix in top production

- The diagonal elements, $\rho(\pm,\pm)$, are given by

$$\rho(+,+) = \mathbf{F_1\, m_t^2 \cot^2}\beta + \mathbf{F_2\, m_b^2 \tan^2}\beta$$
$$\rho(-,-) = \mathbf{F_2\, m_t^2 \cot^2}\beta + \mathbf{F_1\, m_b^2 \tan^2}\beta,$$

- $\mathbf{F_1}$ and $\mathbf{F_2}$ are some kinematical functions of various masses and momenta invovled in the process
- The off-diagonal elements are

$$\rho(+,-) = \rho(-,+) = (\mathbf{m_t^2 \cot^2}\beta - \mathbf{m_b^2 \tan^2}\beta)\mathbf{F_3}$$

- Cross section, $\sigma = \rho(+,+) + \rho(-,-)$
- Polarization, $\mathbf{P_t} \propto \rho(+,+) - \rho(-,-)$

Cross section is plotted as a function of **tan** β and $\mathbf{m_H}$:

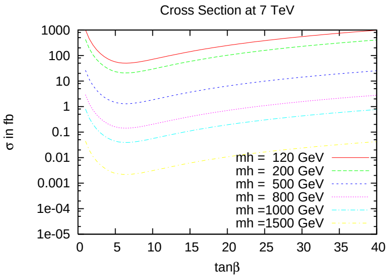

Figure: Cross section at 7 and 14 TeV

Cross section is plotted as a function of $\tan\beta$ and m_H :

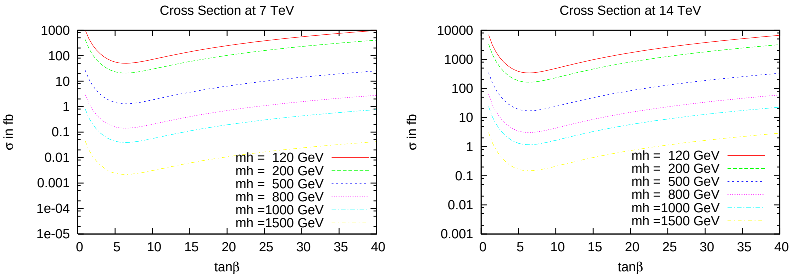

Figure: Cross section at 7 and 14 TeV

- Cross section is proportional to $(\mathbf{m_t^2 \cot^2\beta + m_b^2 \tan^2\beta})$,

Cross section as a function of $\tan\beta$ and m_H

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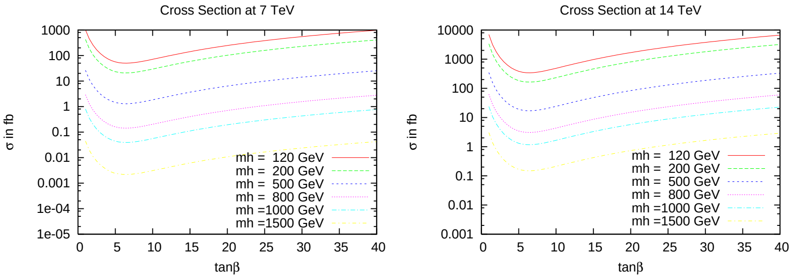


Figure: Cross section at 7 and 14 TeV

- Cross section is proportional to $(m_t^2 \cot^2\beta + m_b^2 \tan^2\beta)$,
- Cross section is minimized at $\tan\beta = \sqrt{m_t/m_b}$

Top polarization P_t is plotted as a function of $\tan\beta$ and m_H :

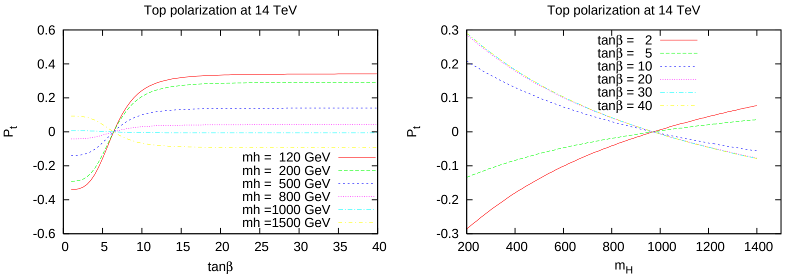


Figure: Top polarization at 14 TeV

Top polarization P_t is plotted as a function of $\tan\beta$ and m_H :

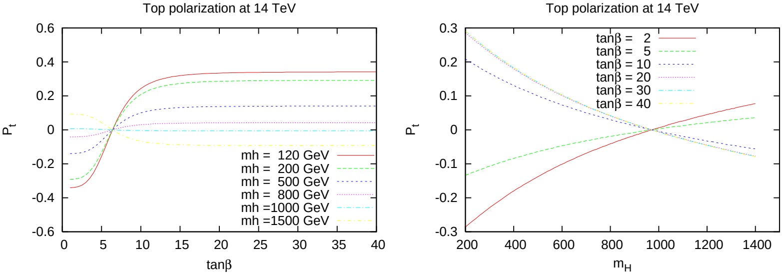


Figure: Top polarization at 14 TeV

- Top polarization is proportional to $(m_t^2 \cot^2\beta - m_b^2 \tan^2\beta)$, Top polarization $\mathbf{P_t}$ is plotted as a function of $\mathbf{tan}\,\beta$ and $\mathbf{m_H}$:

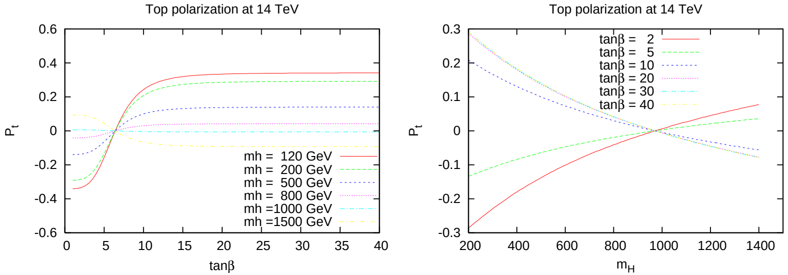


Figure: Top polarization at 14 TeV

- Top polarization is proportional to $(\mathbf{m_t^2 \cot^2}\beta - \mathbf{m_b^2 \tan^2}\beta)$,
- $\mathbf{P_t}$ becomes zero at a fixed value of $\mathbf{tan}\,\beta$, which is $\sqrt{\mathbf{m_t}/\mathbf{m_b}}$,

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

Top polarization P_t is plotted as a function of $\tan\beta$ and m_H :

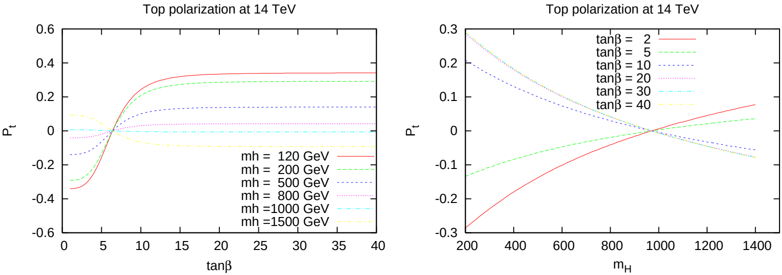


Figure: Top polarization at 14 TeV

- Top polarization is proportional to $(m_t^2 \cot^2\beta - m_b^2 \tan^2\beta)$,
- P_t becomes zero at a fixed value of $\tan\beta$, which is $\sqrt{m_t/m_b}$,
- P_t also zero at a $m_H \sim 6m_t$ independent of $\tan\beta$.

Azimuthal distribution of charged lepton in lab frame

- $\theta_\ell^* \longrightarrow$ angle between top spin and lepton in top rest frame,
- $\theta_{t\ell} \longrightarrow$ angle between top-momentum and lepton in lab frame
- $\phi_\ell \longrightarrow$ angle wrt top production plane, the $\mathbf{x} - \mathbf{z}$ plane,
- The relation between angle θ_ℓ^* between and the angle $\theta_{t\ell}$:

$$\cos\theta_\ell^* = \frac{\cos\theta_{t\ell} - \beta}{1 - \beta\cos\theta_{t\ell}}$$

- $\cos\theta_{t\ell} = \cos\theta_t \cos\theta_\ell + \sin\theta_t \sin\theta_\ell \cos\phi_\ell$

Lab frame angular distribution of the lepton

$$\frac{1}{\Gamma_\ell}\frac{d\Gamma_\ell}{d\cos\theta_{t\ell}} = \frac{1}{2}(1-\beta^2)(1-P_t\beta)\frac{1+\frac{P_t-\beta}{1-P_t\beta}\cos\theta_{t\ell}}{(1-\beta\cos\theta_{t\ell})^3},$$

Azimuthal distribution of charged lepton

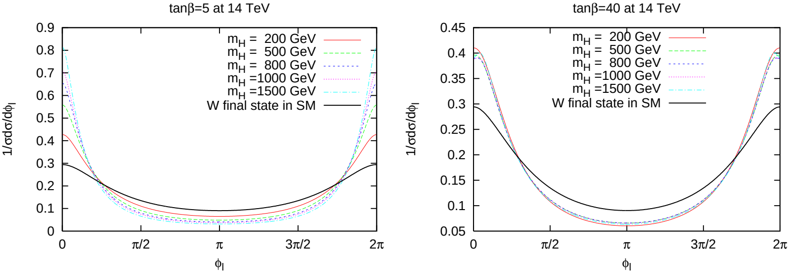


Figure: ϕ_ℓ distribution for different values of $\mathbf{m_H}$ and **SM** process

- At LHC, no unique positive direction of $\mathbf{z}$ axis,
- ϕ_ℓ distribution is identical for $\phi_\mathbf{l}$ and $\mathbf{2\pi} - \phi_\mathbf{l}$ and is symmetric around $\phi_\mathbf{l} = \pi$.
- Boost to lab frame produces a collimating effect along the top momentum, which gives peaking at $\phi_\ell = \mathbf{0}$.

Azimuthal asymmetry of charged lepton

Azimuthal asymmetry of charged lepton is defined as :

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

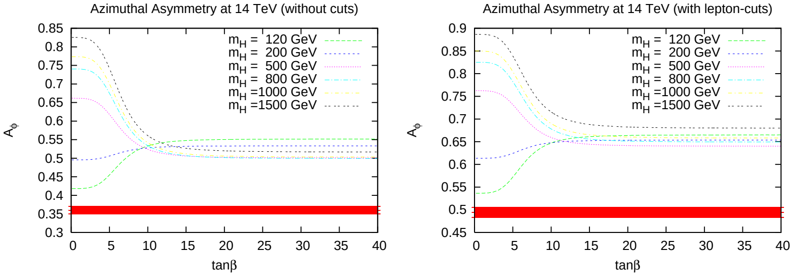


Figure: $\mathbf{A}_\phi$ as a function of $\tan\beta$ and different charged Higgs masses at $\sqrt{s} = 14$ TeV without lepton cuts (left) and with cuts (right).

We have used the following rapidity and transverse momentum acceptance cuts on the decay lepton: $|\eta| < 2.5$, $p_T^\ell > 20$ GeV.

Sensitivity analysis

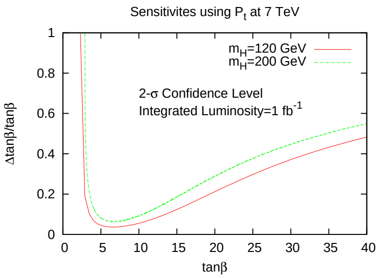
- We investigate the accuracy to which one can determine $\tan\beta$ from $\mathbf{P_t}$, and $\mathbf{A}_\phi$,

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

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

- $\Delta\mathbf{O}(\tan\beta_0)$ is the statistical fluctuation in $\mathbf{O}$ at an integrated luminosity $\mathcal{L}$,
- For $\mathbf{P_t}$ and $\mathbf{A}_\phi$, the statistical fluctuations at a CL $\mathbf{f}$ are given by $\Delta\mathbf{O} = \mathbf{f}/\sqrt{\mathcal{L}\sigma} \times \sqrt{1 - \mathbf{O}^2}$, where $\mathbf{O}$ denotes $\mathbf{P_t}$ or $\mathbf{A}_\phi$.

Sensitivity of Top polarization on $\tan\beta$



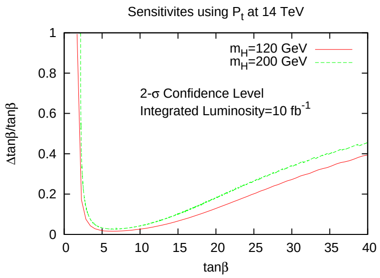


Figure: Sensitivity of $\mathbf{P_t}$ on $\tan\beta$ at 7 TeV and 14 TeV

- We show 2-σ CL sensivity curves for measurement of $\tan\beta$ from $\mathbf{P_t}$,
- We use the criterion $\Delta\tan\beta/\tan\beta < 0.3$ for an accurate determination of $\tan\beta$
- $\mathbf{P_t}$ is the most sensitive for $\tan\beta \sim 3-25$ and $\tan\beta \sim 3-20$ for 7 TeV and 14 TeV LHC respectively.

Sensitivity of Azimuthal asymmetry on $\tan\beta$

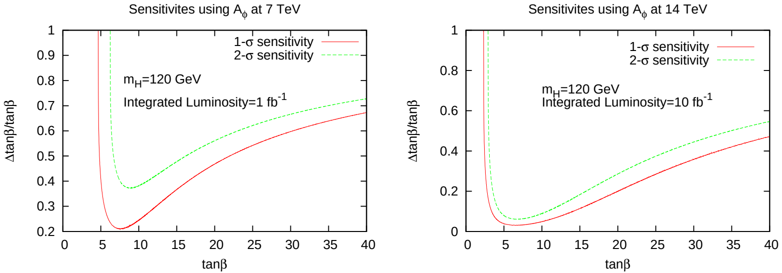


Figure: Sensitivity of $\mathbf{P_t}$ on $\tan\beta$ at 7 TeV and 14 TeV

- We show 1-σ and 2-σ CL sensivity curves for measurement of $\tan\beta$ from $\mathbf{A}_\phi$,
- $\mathbf{A}_\phi$ 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 and Summary

- Top polarization is a very good observable to determine **tan** β,
- Azimuthal distribution of charged lepton shows distinction between various values of **tan** β and the **SM** process,
- Azimuthal asymmetry is a good probe of top polarization and thence of new physics in top production,
- Azimuthal asymmetry can be constructed and is sensitive to low values of **tan** β only,
- Polar distributions of charged lepton and top are not sensitive to **tan** β,

THANKS