H$\longrightarrow \tau^+\tau^-$ at Muon Collider

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Motivation

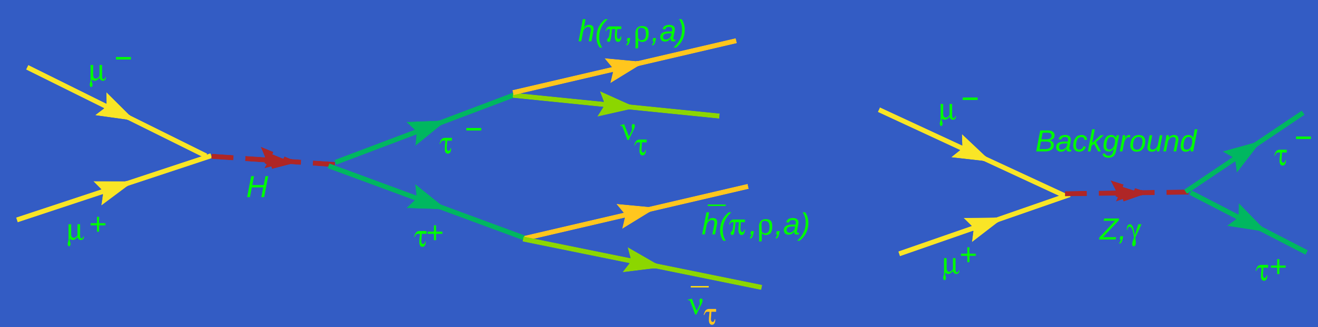
- SM Higgs can have Non-Standard Couplings.
- Many extensions of SM have extra Higgs e.g. SUSY, 2HDM, there are 3 neutral Higgs h, H, A (pseudo-scalar).
- There is interest in Higgs models where certain Higgs only couple to leptons (Leptonic Higgs H.S. Goh., L. J. Hall & P. Kumar arXiv:0902.0814[hep-ph]).

Motivation cont...

- Most general couplings of Higgs to $\tau\ \tau$ pair need to be measured.
- Measurements of these couplings will indicate the nature of the Higgs.
- Muon Collider will be Higgs factory
  $\Rightarrow$ these couplings can be measured precisely.

$H \to \tau^+\tau^-$

- We study $\mu^+\mu^- \to H \to \tau^+(\pi^+\bar{\nu}_\tau)\tau^-(\pi^-\nu_\tau)$ process.



- SM background: $\mu^+\mu^- \to Z, \gamma \to \tau^+\tau^-$.
- Angular distributions (AD) can distinguish Higgs decays and backgrounds(V.Barger hep-ph/0002042).

Non-standard couplings

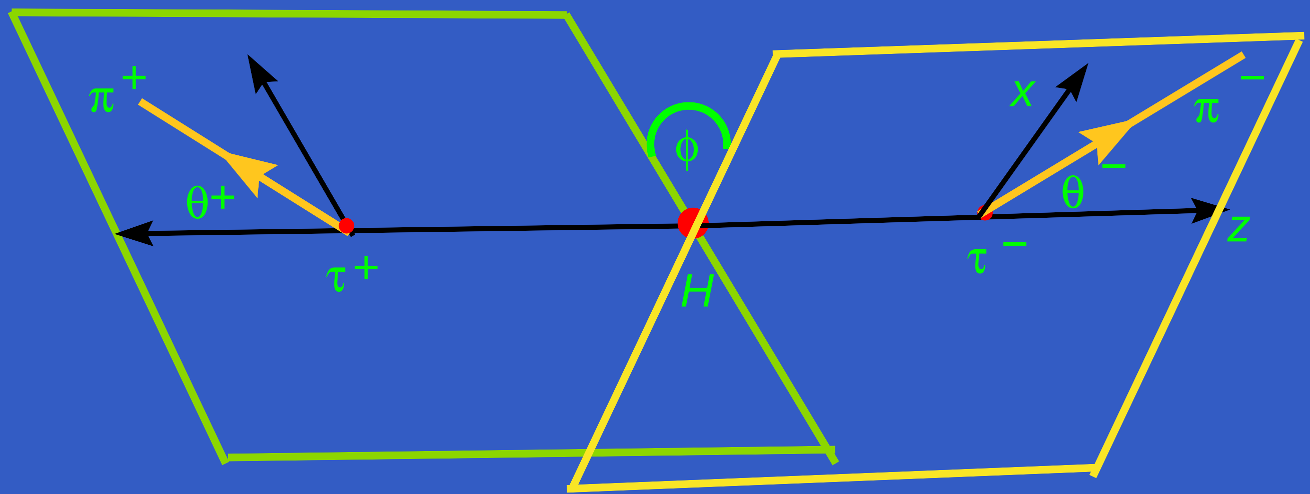
- Non-standard Higgs couplings to τ lepton

$$\mathcal{L} = \bar{\tau}(a + b\gamma_5)\tau.$$

- Various cases
  - SM (scalar Higgs): $a = m_\tau / v$ ($v =$ VEV), b=0.
  - Pseudo-scalar (A) Higgs: $a = 0$, b$\neq$ 0.
  - General case: $a \neq 0$, b$\neq$ 0 and complex

$\Rightarrow$ possible CPV

Full ADs



- Let z-axes lie along $\vec{p}_{\tau^\pm}$ in Higgs rest frame.
- Polar angles in tau rest frame: $\pi^\pm$ - $\theta_{\tau^\pm}$.
- Azimuthal angles: $\pi^\pm$ - $\phi_{\tau^\pm}$ s.t

$$\phi = \phi_{\tau^-} + \phi_{\tau^+}.$$

Full ADs

$$\frac{1}{\Gamma}\frac{d\Gamma(H\longrightarrow\tau^+\tau^-)}{d\cos\theta_{\tau_-}\,d\cos\theta_{\tau_+}\,d\phi} = \frac{1}{8\pi}\Bigg(1-\cos\theta_{\tau_-}\cos\theta_{\tau_+}$$

$$-\beta_\tau\frac{2Re[a_\tau b_\tau^*]}{(\beta_\tau^2|a_\tau|^2+|b_\tau|^2)}(\cos\theta_{\tau_-}-\cos\theta_{\tau_+})$$

$$+\frac{(-\beta_\tau^2|a_\tau|^2+|b_\tau|^2)}{(\beta_\tau^2|a_\tau|^2+|b_\tau|^2)}\sin\theta_{\tau_-}\sin\theta_{\tau_+}\cos\phi$$

$$+\beta_\tau\frac{2Im[a_\tau b_\tau^*]}{(\beta_\tau^2|a_\tau|^2+|b_\tau|^2)}\sin\theta_{\tau_-}\sin\theta_{\tau_+}\sin\phi\Bigg),$$

where $\beta_\tau=\sqrt{1-\frac{4m_\tau^2}{m_H^2}}$.

Full ADs

- For scalar Higgs $b_\tau = 0$

$$\frac{1}{\Gamma}\frac{d\Gamma(H \longrightarrow \tau^+\tau^-)}{d\cos\theta_{\tau_-}\, d\cos\theta_{\tau_+}\, d\phi} = \frac{1}{8\pi}\Big(1 - \cos\theta_{\tau_-}\cos\theta_{\tau_+} - \sin\theta_{\tau_-}\sin\theta_{\tau_+}\cos\phi\Big).$$

- For pseudo-scalar Higgs $a_\tau = 0$

$$\frac{1}{\Gamma}\frac{d\Gamma(A \longrightarrow \tau^+\tau^-)}{d\cos\theta_{\tau_-}\, d\cos\theta_{\tau_+}\, d\phi} = \frac{1}{8\pi}\Big(1 - \cos\theta_{\tau_-}\cos\theta_{\tau_+} + \sin\theta_{\tau_-}\sin\theta_{\tau_+}\cos\phi\Big).$$

Full ADs

- Relative phase between couplings a_τ and b_τ can be probed through coefficients $Re[a_\tau^* b_\tau]$ and $Im[a_\tau^* b_\tau]$

$$
\begin{aligned}
Re[a_\tau^* b_\tau] &= |a_\tau|^2 r_\tau \cos\delta_\tau, \\
Im[a_\tau^* b_\tau] &= -|a_\tau|^2 r_\tau \sin\delta_\tau,
\end{aligned}
$$

  where $r_\tau e^{i\delta_\tau} = b_\tau / a_\tau$.

- $Re[a_\tau^* b_\tau]$ related to forward-backward asymmetry(A_{FB}) and τ polarization (P_T).

Full ADs

- $Im[a_\tau^* b_\tau]$ indicates CP violations.
- In fact, the coefficient of $Im[a_\tau^* b_\tau]$ is the Triple product term.

$$T.P = \hat{p}_{\tau^-}.(\hat{n}_{\pi^-} \times \hat{n}_{\pi^+}) = \sin\theta^H_{\tau^-} \sin\theta^H_{\tau^+} \sin\phi,$$

$\Rightarrow$ T.P $\neq$ 0 indicates CPV.

- T.P is odd under naive time reversal.

$\diamondsuit$ unit vectors

$$\hat{n}_{\pi^\pm} = \frac{\vec{p}_{\pi^\pm}}{|\vec{p}_{\pi^\pm}|}, \; \hat{p}_{\tau^-} = \frac{\vec{p}_{\tau^-}}{|\vec{p}_{\tau^-}|},$$

$\diamondsuit$ $\theta^H_{\tau^\pm}$ polar angles in Higgs rest frame.

Kinematics in Higgs rest frame

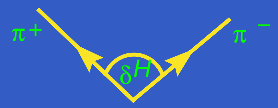
- Relation between polar angles in Higgs and tau rest frames

$$\cos\theta^H_\pm \;=\; \frac{(\beta^H(1+\epsilon^2)+(1-\epsilon^2)\cos\theta_{\tau^\pm})}{((1-\epsilon^2)+\beta^H(1+\epsilon^2)\cos\theta_{\tau^\pm})}.$$

- Polar angles in tau rest frame can be shown as

$$\cos\theta_{\tau_\pm} \;=\; \frac{\frac{2E^H_{\pi^\pm}}{E_\tau}-(1+\epsilon^2)}{\beta_\tau(1-\epsilon^2)}, \quad \epsilon = m_\pi/m_\tau$$

Kinematics in Higgs rest frame



- $\cos\phi$ can be expressed in terms of opening angle (δ^H) between $\pi^\pm$ momenta

$$\cos\phi = \frac{m_h^2}{4m_\tau^2 \sin\theta_{\tau_-} \sin\theta_{\tau_+}} \left(g_-^1 g_+^1 \cos\delta^H - g_-^2 g_2^2 \right),$$

where $g_\mp^1 = ((1 \pm \beta_\tau \beta_\pi \cos\theta_{\tau_\mp})^2 - \frac{16 m_\pi^2}{m_h^2})^{1/2}$

$$g_\mp^2 = (\beta_\pi \cos\theta_{\tau_\mp} \pm \beta_\tau).$$

- Hence AD can be expressed in terms of measurable quantities at Muon collider.

A_{FB} and tau polarization

- $\tau^{\pm}$ polar angular distributions can be obtained as

$$W_{\pm} \;=\; \frac{1}{\Gamma}\frac{d\Gamma(H\longrightarrow\tau^{+}\tau^{-})}{d\cos\theta_{\tau_{\pm}}} = \frac{1}{2}\left(1\pm P_T\cos\theta_{\tau_{\pm}}\right)$$

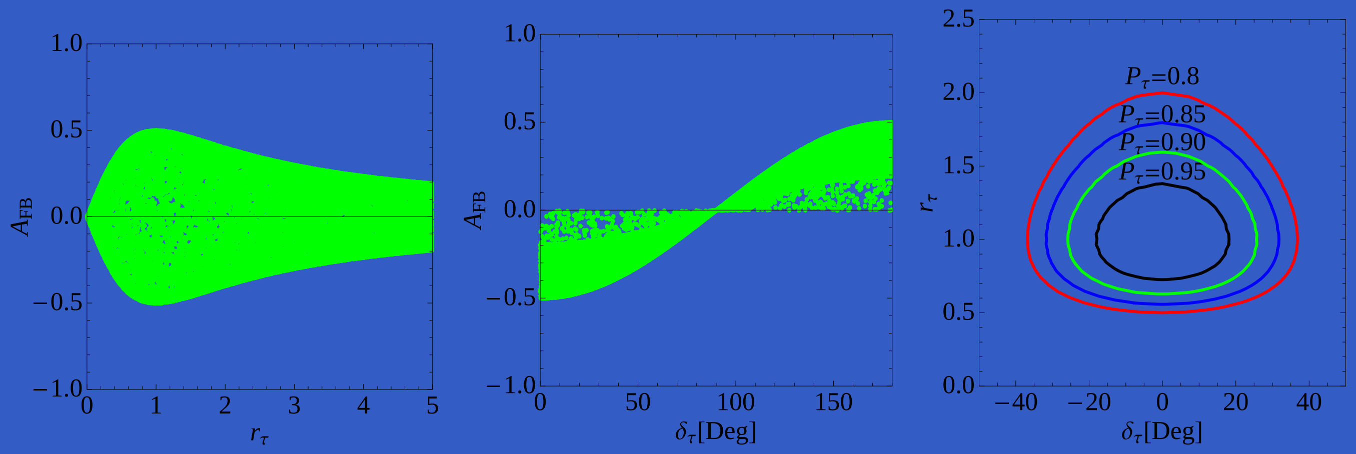
$$\Rightarrow P_T = \frac{2\beta_\tau r_\tau\cos\delta_\tau}{(\beta_\tau^2+r_\tau^2)}$$

- The forward-backward asymmetries define

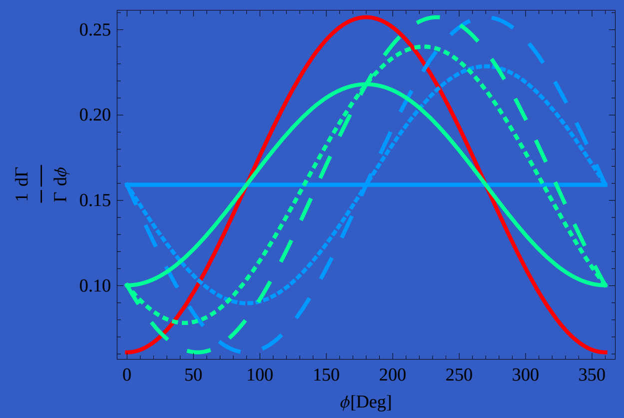
$$A_{FB\pm} = \frac{\int_0^1 d\cos\theta_{\tau_\pm}W_\pm - \int_{-1}^0 d\cos\theta_{\tau_\pm}W_\pm}{\int_0^1 d\cos\theta_{\tau_\pm}W_\pm + \int_{-1}^0 d\cos\theta_{\tau_\pm}W_\pm} = \pm\frac{1}{2}P_T$$

Preliminary results

- A_{FB} and tau polarization measurements can constrain (r_τ, δ_τ)



Preliminary results



$r_\tau = 0, \delta_\tau = 0$, $r_\tau = 0.5, \delta_\tau = 0, \pi/4, \pi/2$, $r_\tau = 1, \delta_\tau = 0, \pi/4, \pi/2$

- Azimuthal angular distribution can be obtained as

$$\frac{1}{\Gamma}\frac{d\Gamma(H\to\tau^+\tau^-)}{d\phi} = \frac{1}{2\pi}\left(1 - \frac{\pi^2}{16}(c_1\cos\phi + c_2\sin\phi)\right),$$

$$c_1 = \frac{1-r_\tau^2}{1+r_\tau},\ c_2 = -\frac{2r_\tau\sin\delta_\tau}{1+r_\tau^2}.$$

- This distribution is sensitive to phase δ_τ.

$H \longrightarrow \tau^- \tau^+$ at LHC

- Problems at LHC are difficult to reconstruct
  - τ rest frame in $\tau \longrightarrow \pi \nu_\tau$ decays.
  - Higgs rest frame ($pp \longrightarrow HX$).

- Muon Collider is preferable for our analysis.

Conclusion

- $H \longrightarrow \tau^-\tau^+$ can be used to study the most general couplings of Higgs to tau lepton.
- Measurements of these couplings can reveal the true nature of the Higgs.
- Future plan: general realistic study (with experimentalists) to see how well we can measure these coupligs at Muon Collider.

THANK YOU