Probing CP violation in $h \to \tau^+\tau^-$ at the LHC

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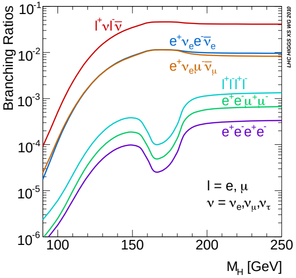
Current experimental results about Higgs

- Mass: $125.6\mathrm{GeV}$.
- Charge, Spin and CP: $Q = 0$, $S = 0$, and favour the CP-even hypothesis.
- Total Decay width: $\lesssim 22\mathrm{MeV}$ @95%. (SM decay width $\sim 4\mathrm{MeV}$)
- Branching ratios in SM:

$\mathrm{Br}(h \to b\bar{b}) = 56.9\%$	$\mathrm{Br}(h \to gg) = 8.5\%$
$\mathrm{Br}(h \to c\bar{c}) = 2.64\%$	$\mathrm{Br}(h \to ZZ^*) = 2.79\%$
$\mathrm{Br}(h \to \tau\bar{\tau}) = 6.28\%$	$\mathrm{Br}(h \to WW^*) = 22.4\%$
$\mathrm{Br}(h \to Z\gamma) = 0.159\%$	$\mathrm{Br}(h \to \gamma\gamma) = 0.229\%$

- Important: the $ht\bar{t}$ interaction has largest coupling!



Mixing of the measured Higgs $h(125)$

Motived by the observation that the $h(125)$ couplings do not deviate much from the SM predictions, we introduce the following simple parameterization of the Higgs mixing,

$$h = \cos\xi\, H + \sin\xi\, A\,, \tag{1}$$

where H is CP-even, and A is CP-odd. The tau lepton can couple to both CP-even Higgs H and CP-odd Higgs A at tree-level, and we assume the CP is conserved separately,

$$\mathcal{L} = -g_{H\tau\tau} H\bar{\tau}\tau - i g_{A\tau\tau} A\bar{\tau}\gamma^5\tau\,, \tag{2}$$

such that the only source of CP violation is because of mixing. The interactions between the mass eigenstate $h(125)$ and the tau-lepton pair is then described by

$$\mathcal{L} = -g_{h\tau\tau} h\big(\bar{\tau}\tau + i\tan(\xi_{h\tau\tau})\bar{\tau}\gamma^5\tau\big)\,, \tag{3}$$

where the overall coupling constant is $g_{h\tau\tau} = g_{H\tau\tau}\cos\xi$, and the effective mixing angle

$$\tan(\xi_{h\tau\tau}) = (g_{A\tau\tau}/g_{H\tau\tau})\tan\xi\,. \tag{4}$$

The CP violation in $h \to \tau^+(\pi^+\bar{\nu}_\tau)\tau^-(\pi^-\nu_\tau)$ is well know. In the Higgs rest frame the squared helicity amplitude is

$$|\mathcal{M}|^2 \propto z_1(1-z_2) + (1-z_1)z_2 - 2\sqrt{z_1(1-z_1)}\sqrt{z_2(1-z_2)}\cos(\phi_1 - \phi_2 + 2\xi_{h\tau\tau})\,. \tag{5}$$

Advantages and disadvantages of $h \to \tau^+(\pi^+\bar{\nu}_\tau)\tau^-(\pi^-\nu_\tau)$

Disadvantages of $h \to \tau^+(\pi^+\bar{\nu}_\tau)\tau^-(\pi^-\nu_\tau)$.

- at least two neutrinos escape the detectors, kinematics are not fully know.
- large irreducible $Z \to \tau^+\tau^-$ backgrounds.
- small τ mass gives small opening angle between π and ν_τ, typically $\Delta R(\pi, \nu_\tau)$ ~ 0.1 (for $E_\tau = 60\text{GeV}$). So the correlation can be easily washed out by detector effects (*e.g.* soft neutral particles in τ-jet).

Advantages of $h \to \tau^+(\pi^+\bar{\nu}_\tau)\tau^-(\pi^-\nu_\tau)$.

- can couple to both CP-even and CP-odd Higgs components at leading order.
- large branching ratio, $\sim 6.28\%$(SM).
- very clean spin correlation in the single charged π decay mode which has a branching ratio $\sim 11\%$.
- large decay length, $\sim 3000\mu\text{m}$ (for τ with energy 60GeV) that make the measurement of impactor parameter possible.

Reconstruction of the full kinematics: use of impact parameter

Impact parameter vectors $\vec{b}_{\pi^\pm}$ are very important because they contains part of the orientation informations of $\tau^\pm$ with respect to $\pi^\pm$ (the $\tau^\pm$ momenta are constrained to be in the plane spanned by $\vec{b}_{\pi^\pm}$ and $\vec{p}_{\pi^\pm}$), which are necessary for observing the azimuthal angle correlation.

When the impact parameter $\vec{b}_{\pi^\pm}$ are measured, the $\tau^\pm$ momenta directions are determined by the massless neutrino condition, $(p_{\tau^\pm} - p_{\pi^\pm}) = 0$ for given $\tau^\pm$ momenta magnitudes $|\vec{p}_{\tau^\pm}|$ which we adopt as our free parameters (*e.g.* for τ^-),

$$\cos\theta_{\tau^-\pi^-} = \frac{2E_{\tau^-}E_{\pi^-} - m_\tau^2 - m_{\pi^-}^2}{2|\vec{p}_{\tau^-}||\vec{p}_{\pi^-}|},$$

$$\frac{\vec{p}_{\tau^-}}{|\vec{p}_{\tau^-}|} = \frac{\vec{b}_{\pi^-} + \frac{|\vec{b}_{\pi^-}|}{\tan\theta_{\tau^-\pi^-}}\frac{\vec{p}_{\pi^-}}{|\vec{p}_{\pi^-}|}}{\left|\vec{b}_{\pi^-} + \frac{|\vec{b}_{\pi^-}|}{\tan\theta_{\tau^-\pi^-}}\frac{\vec{p}_{\pi^-}}{|\vec{p}_{\pi^-}|}\right|},$$

where we have used the condition $\vec{b}_{\pi^-}\cdot\vec{p}_{\pi^-} = 0$. Therefore we we have two basic free parameters $|\vec{p}_{\tau^+}|$ and $|\vec{p}_{\tau^-}|$.

Reconstruction of the full kinematics: probability density functions I

- Because the decay width of Higgs is very small so that the Breit-Wigner distribution is really a δ function. Therefore only one parameter is left effectively. ,

$$\rho_{BW}(|\vec{p}_{\tau^\pm}|) = \frac{N_{BW} m_h^2 \Gamma_h^2}{(m_{\tau\tau}^2 - m_h^2)^2 + m_h^2 \Gamma_h^2} .$$

- If missing transverse momentum $\not{p}_T$, which provide two additional observables, can be measured precisely, the system can be determined completely (even over determined). Unfortunately, on hadron collider, the missing transverse momentum $\not{p}_T$ have very large uncertainty. Therefore instead of solving the system, we maximize the probability density function of the reconstructed missing transverse momentum ${\not{p}_T}^{\text{Reco}} = \vec{p}_{\nu_\tau,T} + \vec{p}_{\bar{\nu}_\tau,T}$ for given $|\vec{p}_{\tau^-}|$ and $\vec{p}_{\tau^+}$,

$$\rho_{\nu}(|\vec{p}_{\tau^\mp}|) = \frac{1}{2\pi\sqrt{|V|}} \exp\left[-\frac{1}{2}(\Delta\not{p}_T)^T V^{-1} (\Delta\not{p}_T) \right] ,$$

where the pseudo-error of the reconstructed missing transverse energy is $\Delta\not{p}_T = \not{p}_T - {\not{p}_T}^{\text{Reco}}$. The expected missing transverse moemtum resolution is represented by the covariance matrix V, which is estimated on an event-by-event basis using a missing transverse momentum significance algorithm.

Reconstruction of the full kinematics: probability density functions II

- In addition, we use the probability density of the distance between neutrino and visible decay product, $\rho_{\Delta R}$ which can be parameterized by the Landau distribution function with an argument $x(|\vec{p}_\tau|) = (\Delta R - \overline{\Delta R}(|\vec{p}_\tau|))/\overline{\sigma}(|\vec{p}_\tau|)$ as

$$\rho_{\Delta R}(|\vec{p}_{\tau^\pm}|) = \frac{\overline{C}}{\sqrt{2\pi}} \exp\left[-\frac{1}{2}(x + e^{-x}) \right].$$

- The total probability density is $\rho = \rho_{BW} \cdot \rho_\nu \cdot \rho_{\Delta R_\tau} \cdot \rho_{\Delta R_{\mp}}$.

Comments:

- Using of ρ_{BW} can introduce bias when we include the background events. Fortunately, almost all the backgrounds have flat azimuthal angle distribution. Therefore the bias cannot affect the experimental sensitivity to the CP violation measurement.
- Because for given $|\vec{p}_{\tau^-}|$ and $|\vec{p}_{\tau^+}|$, ΔRs are already determined. Therefore the density function $\rho_{\Delta R}$ can not improve the reconstruction efficiency. However, it can provide strong constrains on the backgrounds, particularly the QCD jets. In addition, if we allow more quantities, for instance the impact parameter vector free, then $\rho_{\Delta R}$ can provide strong constraint.

Reconstruction of the full kinematics: detector effects and kinematical cuts

The reconstruction of full kinematics are also affected by detector effects, list below are the main sources

- τ-jet: Besides the τ-tag efficiency, the reconstruction is also affected strongly by the soft neutral particles inside of the τ-jet. This is because the distance ΔR between neutrino and pion is very small, typically 0.1, so their relative orientation can be easily washed out by the neutral particles inside of the τ-jet. Therefore the tracks inside of the τ-jet should be used when reconstructing the kinematics.
- Impact parameter: The impact parameter has relatively large error, the typical 1σ resolutions in the transverse and beam directions are

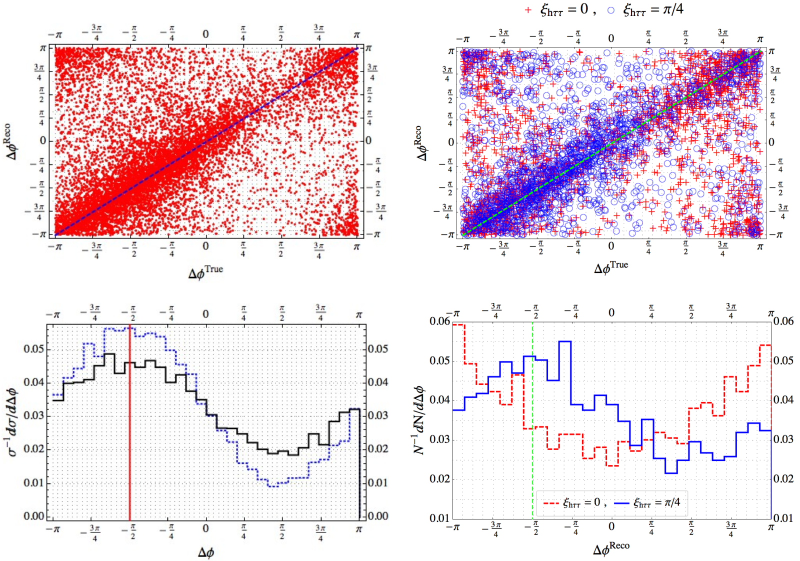
$$\sigma_T(b) = 20\mu\text{m}\,, \quad \sigma_z(b) = 40\mu\text{m}\,.$$

  In our reconstruction, we smear the impact parameters by using these values.

In the event selection, we use the kinematical cuts

- $|\vec{b}_{\pi^\mp}| > 20\mu\text{m}$
- $\eta_{\pi^\mp} < 2.5$, $\min(|\vec{p}_{\pi^\mp,T}|) > 15\text{GeV}$, $\max(|\vec{p}_{\pi^\mp,T}|) > 35\text{GeV}$, $|\not{p}_T| > 45\text{GeV}$, $m_{\tau\tau} > 100\text{GeV}$

Correlation between the real and reconstructed quantities



Expected Num. of events @LHC14 with $\int \mathcal{L} = 3\,\mathrm{ab}^{-1}$

Table : Efficiency and number of events of the processes $pp \to h/Z \to \tau^-\tau^+ \to (\pi^-\nu_\tau)(\pi^+\bar{\nu}_\tau)$ at $14\mathrm{TeV}$ with an integrated luminosity $3\mathrm{ab}^{-1}$.

	Eff.	Evt.(h)	Eff.	Evt.(Z)
No cuts	1.000	1.08×10^5	1.000	5.67×10^7
tau-tag	0.225	2.43×10^4	0.140	7.95×10^6
$\lvert\vec{b}_{\pi^\mp}\rvert > 20\mu m$	0.823	2.00×10^4	0.822	6.54×10^6
$\lvert\eta_{\pi^\mp}\rvert < 2.5$ $\min(\lvert\vec{p}_{\pi^\mp,T}\rvert) > 15\mathrm{GeV}$ $\max(\lvert\vec{p}_{\pi^\mp,T}\rvert) > 35\mathrm{GeV}$ $\lvert\not{p}_T\rvert > 45\mathrm{GeV}$	0.118	2.36×10^3	0.009	5.88×10^4
$m_{\tau\tau} > 100\mathrm{GeV}$	0.900	2.12×10^3	0.200	1.18×10^4

Summary

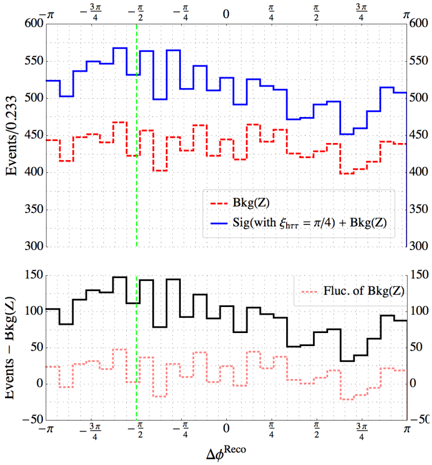
Summary:

- The major $Z \to \tau^+\tau^-$ background is about 5 times larger than the signal events, but can be well predicted by using the data that can be controlled completely.
- Including the major $Z \to \tau^+\tau^-$ backgrounds, we find the experimental sensitivity

$$\Delta\xi_{h\tau\tau} \approx 0.1$$

for $\sqrt{s} = 14\text{GeV}$ with $\int \mathcal{L} = 3\,\text{ab}^{-1}$.

- Comparing to the study in Phys. Rev. **D88**, 076009 (2013), about a factor of 2 is improved.




Thank you.