Probing the Higgs Boson with M_{T2} and MAOS Momentum

K.C., S.Y. Choi, J.S. Lee and C.B. Park
arXiv:0908.0079 [hep-ph]

W.S. Cho, K.C., J.S. Lee and C.B. Park
in preparation

Kiwoon Choi (KAIST)
IPMU Focus Week, Nov. (2009)

Outline

1. Current Strategy for Higgs Boson Search
2. M_{T2}-Assisted On-Shell (MAOS) Momentum
3. Application of MAOS Momentum to the Higgs Search via $H \to WW^* \to \ell\nu\ell\nu$
4. Summary

Current Status of the SM Higgs Search

- LEP bound:

  $$m_H > 114.5 \text{ GeV } (95\% \text{ CL})$$

- Precision EW measurements:

  $$m_H < 186\,(157) \text{ GeV } (95\% \text{ CL})$$

- Tevatron data:

  $$m_H < 160 \text{ GeV} \text{ or } m_H > 170 \text{ GeV } (95\% \text{ CL})$$

$\Longrightarrow$ Most probable range of the SM Higgs boson mass:

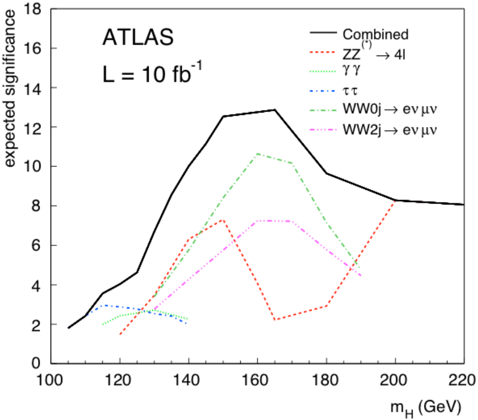
$$\mathbf{114.5 \text{ GeV} < m_H < 160 \text{ GeV}}$$

Major Higgs Search Channels at the LHC

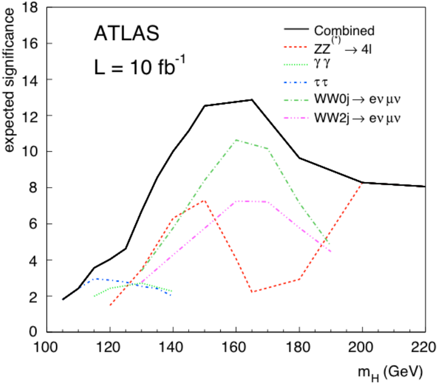
ATLAS Report, arXiv:0901.0512

$$H \to WW^* \to \ell\nu\ell\nu, \quad H \to \gamma\gamma$$
$$H \to ZZ^* \to 4\ell, \quad H \to \tau\bar{\tau}$$

Discovery Significance:



The *WW*-channel plays a dominant role for $m_H > 130$ GeV.



Our Observation: With MAOS momentum (and M_{T2}), the sensitivity of the WW channel can be significantly improved.

$\Longrightarrow$ **(i) significantly enhance the efficiency of the Higgs search and mass measurement over the mass range** $115\,\text{GeV} < m_H < 190\,\text{GeV}$.

(ii) make the WW-channel as important as the $\gamma\gamma$ or $\tau\bar{\tau}$ channel for $m_H < 130\,\text{GeV}$.

Current Search Strategy for $H \to WW^* \to \ell\nu\ell\nu$

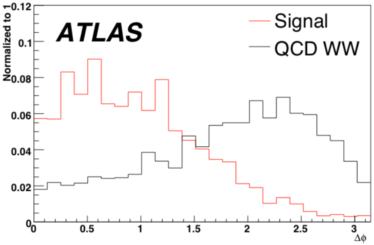
ATLAS Report, arXiv:0901.0512

How to suppress the backgrounds and which observables are (most) sensitive to the Higgs signals (i.e. to m_H)?

- Backgrounds: $pp \to WW$, $t\bar{t}$, single top, $Z \to \ell\bar{\ell}$, ...

  These backgrounds, except for WW, can be suppressed enough by the basic selection cut on $\{\, p_T^\ell,\ p_T^{\text{jet}},\ p_T^{WW},\ E_T^{\text{miss}},\ m_{\ell\ell}\,\}$.

- Remained WW backgrounds can be controlled by $\Delta\Phi_{\ell\ell}$ (transverse dilepton opening angle) which encodes the Higgs spin correlation:



Use large angle events ($\Delta\Phi_{\ell\ell} > 1.6$) as control region and small angle events ($\Delta\Phi_{\ell\ell} < 1.6$) as signal region.

- Use the transverse mass of $WW \to \ell\nu\ell\nu$ as the main observable to probe the Higgs signals.

  Transverse mass has been used often as an alternative to the invariant mass for events with missing energy:

$$M_T^2(WW) = m_{\ell\ell}^2 + m_{\nu\nu}^2 + 2\sqrt{|\mathbf{p}_T^{\ell\ell}|^2 + m_{\ell\ell}^2}\sqrt{|\mathbf{p}_T^{\nu\nu}|^2 + m_{\nu\nu}^2} - 2\mathbf{p}_T^{\ell\ell} \cdot \mathbf{p}_T^{\nu\nu}$$

$$(\mathbf{p}_T^{\nu\nu} = \mathbf{p}_T^{WW} - \mathbf{p}_T^{\ell\ell} = \not{p}_T)$$

  As $m_{\nu\nu}$ is not available, one considers a variant:

$$\begin{aligned} M_T^{\text{approx}} &= M_T\big|_{m_{\nu\nu}=m_{\ell\ell}} && \text{(Rainwater and Zeppenfeld)} \\ \text{or} \quad M_T^{\text{true}} &= M_T\big|_{m_{\nu\nu}=0} && \text{(Barr, Gripaios, Lester)} \end{aligned}$$

  M_T^{true} has a slightly better efficiency than M_T^{approx}, but almost the same for the light Higgs mass range $m_H < 160$ GeV.

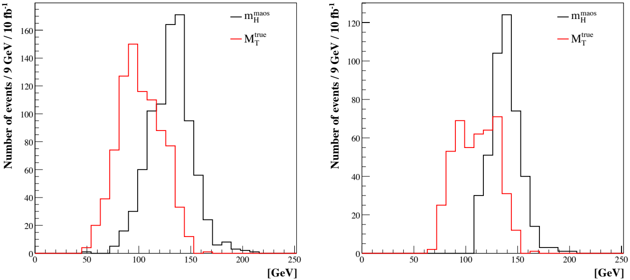
  Barr, Gripaios, Lester; ATLAS Higgs Search Group

Our Proposal:

(i) Use $(m_H^{\rm maos})^2 = (p_\ell + p_{\bar\ell} + p_\nu^{\rm maos} + p_{\bar\nu}^{\rm maos})^2$ as the main observable to probe the Higgs signals.

(ii) Use M_{T2} as an additional event selection variable.

- m_H = Central Peak of $m_H^{\rm maos}$ = Endpoint of $M_T^{\rm true}$



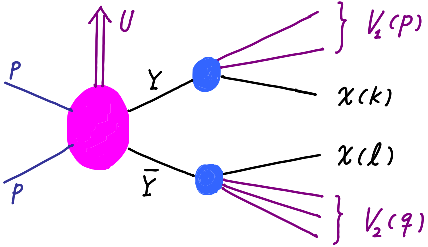
basic + angle cut ($m_H = 140$) basic + angle + M_{T2} cut

- The shape of $m_H^{\rm maos}$-distribution and the S/B ratio can be efficiently controlled by the M_{T2} cut.

M_{T2}-Assisted-On-Shell (MAOS) Momentum

Cho, KC, Kim, Park, arXiv:0810.4853; KC, Choi, Lee, Park, arXiv:0908.0079

MAOS momentum is a kinematic variable designed to approximate systematically the invisible particle momenta in generic events producing two invisible particles with the same mass.



$$pp \to H + U(\text{ISR}) \to W + W^* + U \to \ell(p) + \bar{\nu}(k) + \bar{\ell}(q) + \nu(l) + U$$

Construction of the MAOS neutrino momenta $\mathbf{k}_\mu^{\rm maos}$ & $\mathbf{l}_\mu^{\rm maos}$ for

$$W(p+k)W^*(q+l) \to \ell(p) + \nu(k) + \ell(q) + \nu(l)$$

$\mathbf{M_{T2}}$: Lester and Summers

$$\begin{aligned} & M_{T2}(\mathbf{p}_T, \mathbf{q}_T, \not{\mathbf{p}}_T) \\ = & \min_{\mathbf{k}_T+\mathbf{l}_T=\not{\mathbf{p}}_T} \left[\max\Big(M_T(\mathbf{p}_T, \mathbf{k}_T), M_T(\mathbf{q}_T, \mathbf{l}_T) \Big) \right] \end{aligned}$$

- Determine the transverse components with M_{T2} and $\not{\mathbf{p}}_T$:

$$M_{T2} = M_T(\mathbf{p}_T, \mathbf{k}_T^{\rm maos}) = M_T(\mathbf{q}_T, \mathbf{l}_T^{\rm maos}), \quad \not{\mathbf{p}}_T = \mathbf{k}_T^{\rm maos} + \mathbf{l}_T^{\rm maos}$$

- Determine the longitudinal and energy components with (pseudo) on-shell conditions:

$$\begin{aligned} & (k^{\rm maos})^2 = (l^{\rm maos})^2 = 0 \\ & (p + k^{\rm maos})^2 = (q + l^{\rm maos})^2 = M_{T2}^2 \quad (m_H < 2M_W) \end{aligned}$$

- **MAOS momenta are designed to have $\mathbf{k}_\mu^{\rm maos} = \mathbf{k}_\mu^{\rm true}$ & $\mathbf{l}_\mu^{\rm maos} = \mathbf{l}_\mu^{\rm true}$ for the M_{T2} endpoint events for both signals and backgrounds:**

  * Since a relatively large fraction of events are near the endpoint, particulary after p_T and $E_T^{\rm miss}$ cuts, MAOS momenta provide a reasonably good approximation to the true neutrino momenta.

  * One can systematically improve the accuracy of the MAOS approximation with an appropriate M_{T2} cut: $M_{T2} > M_{T2}^{\rm low}$

  * Distribution of $m_H^{\rm maos}$ for signal events has a narrow peak at $m_H^{\rm true}$ under a proper M_{T2}-cut selecting the near endpoint events:

$$(m_H^{\rm maos})^2 = (p + q + k^{\rm maos} + l^{\rm maos})^2$$

- $M_{T2}^{\rm max}(\text{signal}) = m_H/2 \, < \, M_W, \quad M_{T2}^{\rm max}(\text{background}) = M_W$

  * For m_H significantly lower than $2M_W$, one can employ an upper M_{T2}-cut, $M_{T2} \, < \, M_{T2}^{\rm high} \, \sim \, m_H/2$, to reduce the backgrounds without touching the signals.

- **Correlation between $\Delta\Phi_{ll}$ and M_{T2}:**

  $$M_{T2}^2 = 2|\mathbf{p}_T||\mathbf{q}_T|\left(1 + \cos\Delta\Phi_{ll}\right) \text{ for vanishing ISR}$$

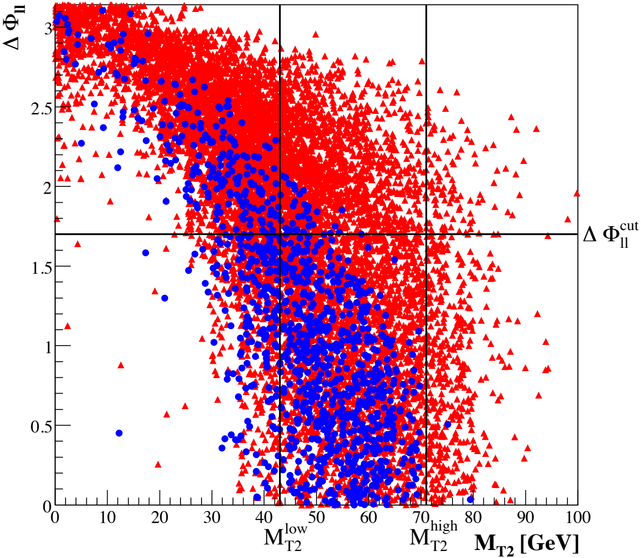
  * The angle cut, $\Delta\Phi_{\ell\ell} < \Delta\Phi^{\rm cut}$, selects events with higher M_{T2}, thus improve not only the S/B ratio, but also the accuracy of the MAOS approximation to neutrino momenta.

  One can employ appropriate $\Delta\Phi_{\ell\ell}$ and M_{T2} cuts:

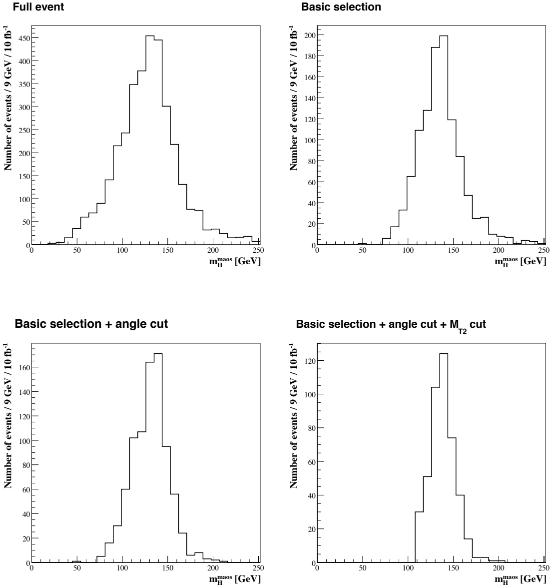
  $$\Delta\Phi_{\ell\ell} < \Delta\Phi^{\rm cut}, \qquad M_{T2}^{\rm low} < M_{T2} < M_{T2}^{\rm high}$$

  to optimize the S/B ratio and the accuracy of the MAOS momentum approximation (= narrow peak of $m_H^{\rm maos}$).

Scatter plot of $\Delta\Phi_{\ell\ell}$ and M_{T2} after the basic selection cut (signal for $m_H = 140$ GeV and background)

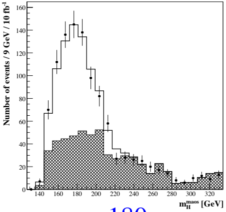


Distribution of m_H^{maos}(signal) under the angle and M_{T2} cuts ($m_H = 140$ GeV)

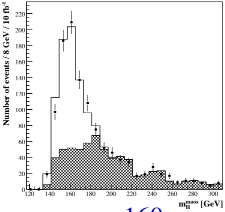


Distributions of m_H^{maos} (signal+background)

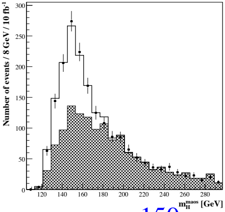
- Event generation with PYTHIA6.4 with $\int L\,dt = 10\ \text{fb}^{-1}$
- Include $q\bar{q}, gg \to WW$ and $t\bar{t}$ backgrounds
- Detector simulation with PGS4
- Event selection including the optimal cut of M_{T2} and $\Delta\Phi_{ll}$



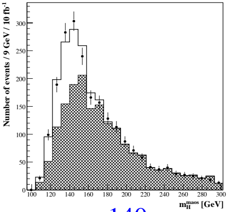
$m_H = 180$



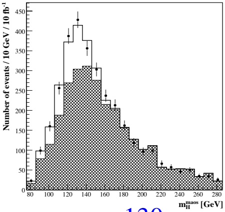
$m_H = 160$



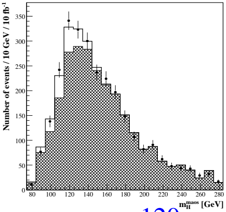
$m_H = 150$



$m_H = 140$

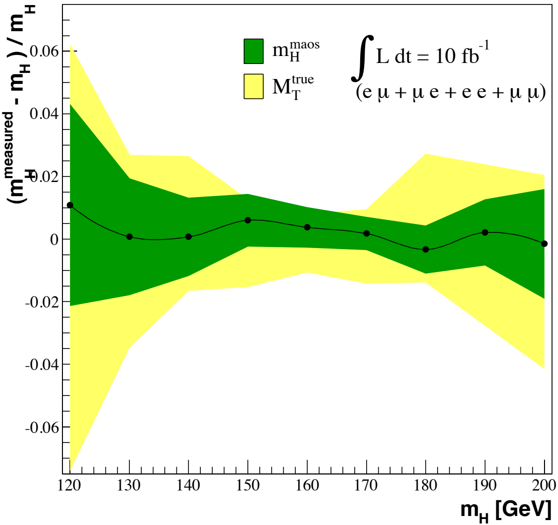


$m_H = 130$



$m_H = 120$

1-σ error of m_H from the likelihood fit to m_H^{maos} or M_T^{true}



A similar improvement of the discovery significance is expected.

Cho, KC, Lee, Park, in preparation

Summary

- MAOS momenta provide a systematic approximation to the invisible particle momenta in missing energy events, which can be useful for the SM processes

  $$H \to W^+W^- \to \ell^+\nu\ell\bar{\nu},$$
  $$t\bar{t} \to bW^+\bar{b}W^- \to b\ell^+\nu\bar{b}\ell\bar{\nu},$$

  as well as the new physics processes producing a pair of invisible WIMPs in the final state.

- Indeed, with MAOS momentum and M_{T2} applied to $H \to WW^* \to \ell\nu\ell\nu$, the efficiency of the Higgs search and mass measurement can be significantly improved for the most probable Higgs mass range: $115\,\mathrm{GeV} < m_H < 160\,\mathrm{GeV}$.