The status of Missing Mass Calculator for Higgs boson mass estimation in the ATLAS $H \rightarrow \tau \tau$ analysis

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Among the Standard Model (SM) Higgs boson decays to fermions, $H \rightarrow \tau \tau$ is the second most frequent one (BR 6.32%). See the talk by Pier-Olivier DeViveiros.

Large Yukawa coupling to $\tau$-leptons enables direct measurement and examination of the Higgs boson properties (decay width, spin, parity, etc.).

The ATLAS $H \rightarrow \tau \tau$ analysis focuses on measurements of the fiducial and differential cross sections on four Higgs boson production processes: $ggF$, VBF, $VH$, and $t\bar{t}H$.

$H \rightarrow \tau \tau$ cross section was measured with the data collected in 2015 and 2016 [2].
The Higgs boson mass in $H \rightarrow \tau\tau$ SM analysis

- Background processes mimic $H \rightarrow \tau\tau$,
  - Drell-Yan $Z \rightarrow \tau\tau$ (50-90% of the total background)
  - QCD jets misidentified as $\tau_{\text{had}}, \mu, \epsilon$
- Accurate ditau mass $m_{\tau\tau}$ reconstruction is necessary for reasonable separation between the signal $H \rightarrow \tau\tau$ process and the largest irreducible background $Z \rightarrow \tau\tau$ events: mass distributions of $Z$ and $H$ bosons partially overlap.
  - The use of the mass $m_{\tau\tau}$ as a discriminant in the final fit for $H\tau\tau$ coupling analysis.
  - The CP determination (see Alena Loesle’s talk) also uses $m_{\tau\tau}$ as input to the multi-variate analysis discriminant
- A mass estimator also needs to be fast and versatile.

Figure: Distribution of the reconstructed ditau invariant mass ($m_{\tau\tau}$) for the sum of all signal regions. [2].
The \( m_H \) estimation in the \( H \rightarrow \tau\tau \) process

**Figure:** The \( H \rightarrow \tau_{\text{lep}}\tau_{\text{had}} \) decay cascade.

- \( \tau \)-leptons instantly decay with the non-detectable neutrinos in the final state:
  - Had-had \( H \rightarrow \tau_{\text{had}}\tau_{\text{had}} \) (\( H \rightarrow \tau\tau \rightarrow hh + 2\nu \)) channel – BR 42.0%
  - Lep-had \( H \rightarrow \tau_{\text{lep}}\tau_{\text{had}} \) (\( H \rightarrow \tau\tau \rightarrow lh + 3\nu \)) channel – BR 45.6%
  - Lep-lep \( H \rightarrow \tau_{\text{lep}}\tau_{\text{lep}} \) (\( H \rightarrow \tau\tau \rightarrow ll + 4\nu \)) channel – BR 12.4%

- The ditau invariant mass, \( m_{\tau\tau}^{\text{MMC}} \), is estimated based on the 4-vectors of the visible \( \tau \)-decay products, missing transverse energy \( E_{T}^{\text{miss}} \) (or \( E_T' \)) as the neutrino system momentum proxy, and the event info.

- In the ATLAS \( H \rightarrow \tau\tau \) analysis, \( m_{\tau\tau} \) is calculated by the Missing Mass Calculator (MMC) method, an advanced likelihood-based technique.
  - Applied in the \( ggF/VBF \) analysis.

**Figure:** The ditau decay channels and their probability.
The Missing Mass Calculator (MMC) technique

- Originally developed by the CDF collaboration at Tevatron → adopted by the ATLAS experiment.
- Accounts for the kinematic constraints while considering the variation of energy and position of the particles in the decay cascades over the allowed phase space.
  - Assumes neutrinos are the only $E_{\text{miss}}$ source.
  - For each event, scan over possible configurations of the visible and invisible $\tau$-decay products is performed in a Markov chain.
  - For each kinematic configuration, the final weight is defined as a log-likelihood of its total probability.
- The solution with the highest likelihood and largest weight is set as a final estimator of $m_{H}$.

\[
\mathcal{L} = - \log(P_{\text{total}}) = - \log(P(\Delta R_{\text{vis,miss}}_{1,p_{\tau}}, \delta_{\phi_{1}}) \times P(\Delta R_{\text{vis,miss}}_{2,p_{\tau}}, \delta_{\phi_{2}}) \times P(E_{T,x,y}) \times P(E_{\text{vis. }\tau_{1}}) \times P(E_{\text{vis. }\tau_{2}}) \times P(m_{\text{miss}1}) \times P(m_{\text{miss}2})
\]

Figure: Example of the probability distribution functions $P(\Delta R, p_{\tau})$ [3] at a particular $p_{\tau}$.
The assumption that the $E_T^{\text{miss}}$ is only due to neutrino presence requires appropriate treatment of the $E_T^{\text{miss}}$ resolution due to e.g., $E_T^{\text{miss}}$ resolution smearing, restrictions in the track-based soft term reconstruction [4].

$$P(E_T^{x,y}) = P(E_{\text{sugg}}^{T x,y}, E_{\text{meas}}^{T x,y}, \sigma_{E_T^{\text{miss}}}) = \exp(-\frac{(\Delta E_T^{x,y})^2}{2\sigma_{E_T^{\text{miss}}}^2}) \ [3]$$

$E_T^{\text{miss}}$ resolution estimated as the RMS width of $E_{T x,y}^{\text{reco}} - E_{T x,y}^{\text{truth}}$.

The standard MMC approach relies on the $E_T^{\text{miss}}$ resolution parametrization depending on underlying event activity ($\sum E_T$) [6], pile-up ($N_{PV}$ or $\langle \mu \rangle$), and, for lep-lep channel, kinematics of the visible $\tau$-lepton decay products.

The method assumes the $E_T^{\text{miss}}$ to be isotropic. It needs to be re-parameterized to accommodate the properties of each new dataset.
$E_T^\text{miss}$ resolution estimation in the MMC method (1)

Alternative $E_T^\text{miss}$ resolution estimations for input to the MMC were evaluated:

- A new method from the ATLAS $E_T^\text{miss}$ group [7] provides an object-based $E_T^\text{miss}$ significance calculation that uses the resolution of all input objects.

- The significance can be used for per-event $\sigma_{E_T^\text{miss}}$ estimation:

$E_T^\text{miss} / S_{E_T^\text{miss}}$, where $S_{E_T^\text{miss}}$ is the object-based $E_T^\text{miss}$ significance.

- $\sigma_\parallel$, $\sigma_\perp$, $\rho''$, where $\sigma_\parallel$ and $\sigma_\perp$ are the parallel and perpendicular components of $E_T^\text{miss}$ resolution, respectively, and $\rho$ is their correlation.

General anisotropy of the actual $E_T^\text{miss}$ is in the $E_T^\text{miss}$ PDF:

$$
P(E_{\text{sugg}}^\parallel, E_{\text{sugg}}^\perp, E_{\text{meas}}^\parallel, E_{\text{meas}}^\perp, \sigma_\parallel, \sigma_\perp, \rho) = \frac{1}{2\pi\sigma_\parallel\sigma_\perp\sqrt{1-\rho^2}} \times \exp\left\{-\frac{1}{2(1-\rho^2)}\left[\frac{E_{\text{sugg}}^\parallel - E_{\text{meas}}^\parallel}{\sigma_\parallel}\right]^2 + \left(\frac{E_{\text{sugg}}^\perp - E_{\text{meas}}^\perp}{\sigma_\perp}\right)^2 - 2\rho\left(\frac{E_{\text{sugg}}^\parallel - E_{\text{meas}}^\parallel}{\sigma_\parallel}\right)\left(\frac{E_{\text{sugg}}^\perp - E_{\text{meas}}^\perp}{\sigma_\perp}\right)\right\}
$$

*Figure:* The $E_T^\text{miss}$ resolution [5].

*Figure:* Background rejection vs. signal efficiency [7].

*Figure:* $m_{\tau\tau}^{\text{MMC}}$ in $H \rightarrow \tau_{\text{lep}}\tau_{\text{lep}}$ events [8].
$E_{\text{miss}}^T$ resolution estimation in the MMC method (2)

- The tool separation power remains at the same level: $\sim 80\%$ of $Z \rightarrow \tau \tau$ rejection at the $ggH$ signal acceptance of $\sim 80\%$.
- $E_{\text{miss}}^T$ resolution estimation via $S_{E_{\text{miss}}^T}$ is preferable as:
  - Dataset- and process-independent approach accounting for all the $E_{\text{T}}$ components resolution.
  - Such approach is compliant with the up-to-date ATLAS $E_{\text{T}}$ definition and gives an advantage for physics analysis, e.g. jet background is accounted in $\sigma_{E_{\text{T}}}^\text{miss}$ as proportionally growing with pile-up jets number [7].

![Figure](image_url)

**Figure:** ROC curve for selecting $H \rightarrow \tau_{\text{lep}} \tau_{\text{lep}}$ events and rejecting $Z \rightarrow \tau_{\text{lep}} \tau_{\text{lep}}$ events [8].
The number of steps for the phase space scan in the Markov chain was tuned for Run 1 conditions (200 k).

Studies were carried to verify whether a smaller number of iterations was sufficient for Run 2 conditions.

Figure: $m_{\tau\tau}^{\text{MMC}}$ in $Z \rightarrow \tau\tau$ and $H \rightarrow \tau\tau$ events [8].

Figure: The CPU time of the $m_{\tau\tau}^{\text{MMC}}$ calculation [8].

Gain in computational time.
Phase space scanning in the MMC method (2)

- The $N_{\text{iter}}$ in the phase space scan with reducing optimized by a factor of $\sim 4$.
- $m_{H}^{\text{MMC}}$ resolution is $\sim 16-17$ GeV – stable for all $N_{\text{iter}}$ above 50k.
- The AUC values are in a good agreement for 50k, 100k, 200k iterations. The power of separation between signal and background is kept.

**Figure:** The $m_{\tau\tau}^{\text{MMC}}$ resolution in as a function of $N_{\text{iter}}$ [8].

**Figure:** The AUC of the ROC curve as a function of $N_{\text{iter}}$ [8].

**Figure:** The relative AUC of the ROC curve as a function of $N_{\text{iter}}$ [8].
Conclusions

- Different methods were investigated for estimating the $E_T^{\text{miss}}$ resolution in the ATLAS Missing Mass Calculator.
  - The alternative approach for $E_T^{\text{miss}}$ resolution estimation was introduced and tested: $E_T^{\text{miss}}$ resolution as $E_T^{\text{miss}} / S_{E_T^{\text{miss}}}$, where $S_{E_T^{\text{miss}}}$ is the object-based $E_T^{\text{miss}}$ significance.
- Up-to-date ATLAS estimation of $E_T^{\text{miss}}$.
- No requirement for retuning with a new dataset.
- The CPU time was reduced by a factor of $\sim 4$ due to optimization of the phase space scanning procedure.
- The performance of the updated MMC method was verified.
  - The $m_{\tau\tau}^{\text{MMC}}$ shape and width are adequate.
  - The $m_H^{\text{MMC}}$ resolution is at the level of $\sim 16$ and $\sim 17$ GeV (in the had-had and lep-lep channels, respectively).
  - The technique provides $\sim 80\%$ of $Z \rightarrow \tau\tau$ rejection at the $ggH$ signal acceptance of $\sim 80\%$ working point.
- The updated MMC version will be used for the $H \rightarrow \tau\tau$ analysis with the full ATLAS Run 2 dataset.
1. https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG#Higgs_cross_sections_and_decay_b

2. Cross-section measurements of the Higgs boson decaying into a pair of $\tau$-leptons in proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector. 0.1103/PhysRevD.99.072001


4. Performance of missing transverse momentum reconstruction with the ATLAS detector using proton–proton collisions at $\sqrt{s}=13$ TeV. 10.1140/epjc/s10052-018-6288-9


6. Search for anomalous production of events with two photons and additional energetic objects at CDF. 10.1103/PhysRevD.82.052005


8. MMC performance studies Run 2. ATLAS-TAU-2019-001
Bonus slides
$m_{\tau\tau}^{\text{MMC}}$, phase space scan

**Figure:** The Markov chain scan principle.

**Figure:** $m_{\tau\tau}^{\text{MMC}}$ in $H \rightarrow \tau_{\text{had}} \tau_{\text{had}}$ events.