Tau Physics in ATLAS

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• Tau Physics at the LHC
• ATLAS experiment
• Tau Identification
• $Z \rightarrow \tau\tau$ Cross Section Measurement
• $W \rightarrow \tau\nu$ Cross Section Measurement
• Search for MSSM Higgs $\rightarrow \tau\tau$
• Conclusion
• Tau is the heaviest of the three sequential leptons
  - electron, muon, tau
• Tau is heavy and decays inside our detectors
  - $m_\tau = 1.777$ GeV
  - $c\tau = 87\ \mu$m
• Tau decays to:
  - electrons and muons (35%)
    • generally indistinguishable from directly produced electrons and muons → not covered as part of “LHC tau physics”
  - hadrons (65%); generally one or more $\pi^\pm$ possibly accompanied by $\pi^0$s
• Taus are especially interesting for cases where coupling to third generation is expected to be enhanced
  - In particular Higgs: coupling to mass

Typical detector signature:
• one or three (collimated) charged tracks
• collimated energy deposits
• possible secondary vertex reconstruction/large impact parameter
The ATLAS Experiment at the LHC

- 3000 scientists
- 38 countries
- 100 M readout channels
- tracking inside 2 Tesla magnetic field
- hermetic, fine-grained calorimeter system
- muon spectrometer
- pp collisions at $\sqrt{s} = 7$ TeV
- instantaneous luminosity $10^{30} - 2 \times 10^{33}$ cm$^{-2}$s$^{-1}$
**ATLAS Detector Subsystems**

**Tracking system**

Inside 2.0 Tesla magnetic field
- **Silicon**: Pixel and SCT
- Straw tube **drift chambers**: TRT
  - Also transition radiation: electron identification

**Calorimeter system**

Electromagnetic calorimeter \([\Delta \phi \times \Delta \eta = 0.025 \times 0.025]\)
- Liquid Argon

Hadronic calorimeter \([\Delta \phi \times \Delta \eta = 0.1 \times 0.1]\)
- **Tile calorimeter** in barrel
- Liquid Argon in endcaps

**Fine-grained calorimeter system:** Important for reconstruction of transverse shower profile of tau decays and jets
Tracks are matched to jet seeds; discriminating variables are calculated from the combined tracking and calorimeter information:

- 1 or 3 prong signature
- Narrow clustering of tracks and calorimeter deposits
- Tau flight time

Tau Identification Performance

Three discriminants:
1. $p_T$-parametrized cuts
2. Boosted Decisions Trees
3. Projective Likelihood

Output scores of multivariate methods

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3 prongs $15 \text{ GeV} < p_T < 60 \text{ GeV}$

2010 dijet data $\int dt L = 23 \text{ pb}^{-1}$

Performance

1-prong

3-prong

[2] ATLAS: Tau Public Results
The Dataset

Nov 2010: Observation of $W \to \tau_h \nu$
Feb 2011: Observation of $Z \to \tau \tau \to \ell \tau_h$
July 2011: Measurement of $Z \to \tau \tau$ cross section (2010 data)
Aug 2011: Measurement of $W \to \tau \nu$ cross section (2010 data)
Aug 2011: Search for neutral MSSM Higgs boson decaying to $\tau \tau$ (2011 data)

$\tau_h = \text{hadronic tau decay}$

ATLAS Online Luminosity

$\sqrt{s} = 7\text{ TeV}$

LHC Delivered All
LHC Delivered Stable
ATLAS Ready Recorded

2010

2011

30-40 $\text{pb}^{-1}$

$\geq 2\text{ fb}^{-1}$
**Z→ττ Cross Section Measurement**

Based on 36 pb\(^{-1}\) of 2010 data.

Final states: e\(\mu\), \(\mu\mu\), e\(\tau_h\), and \(\mu\tau_h\).

Here, concentrate on semileptonic channels \(\ell\tau_h\).

\(Z\rightarrow\tau\tau\rightarrow\ell\tau_h\) event selection:

- Lepton trigger
- One e/\(\mu\) with \(p_T > 16/15\) GeV
- \(\tau_h\) with \(p_T > 20\) GeV
- Opposite charge
- Suppress QCD multijets: Tight lepton isolation
- Suppress W background: \(\sum \cos \Delta \phi > -0.15\)

\[
\sum \cos \Delta \phi = \cos[\phi(\ell) - \phi(E_T^{\text{miss}})] + \cos[\phi(\tau_h) - \phi(E_T^{\text{miss}})]
\]

Quantifies if the \(E_T^{\text{miss}}\) is between the decay products

Z\rightarrow\tau\tau - Backgrounds

- Normalize $W \rightarrow \ell\nu + \text{jets}$ Monte Carlo using high $m_\tau$ data
- Other EW backgrounds estimated from Monte Carlo
- QCD estimate is data-driven, scaling SS data by $R_{\text{OS/SS}}$, measured in non-isolated (multi-jet rich) data sample, correcting for EW contamination with Monte Carlo
  - ABCD Method

\[ N^A = N^B \cdot \frac{N^C}{N^D} = N^B \cdot R_{\text{OS/SS}} \]
$\sigma_{\text{combined}} = 0.97 \pm 0.07(\text{stat.}) \pm 0.07(\text{sys.}) \pm 0.03(\text{lumi.})$ nb

$\sigma_{\text{theory}} = 0.96 \pm 0.05$ nb at NNLO

Systematics:
- $\tau_h$ energy scale 11%
- $\tau_h$ efficiency 8.6%
- $\mu$ efficiency 8.6%
- e efficiency 5-9%
- acceptance 3%
- luminosity 3.4%

*) Efficiency and energy scale derived from simulation. Systematics from variations in detector geometry, hadronic showering model, underlying event model, noise thresholds, etc.

• $p_T(T_h) = 20 - 60$ GeV
• $E_{miss} > 30$ GeV
• Missing $E_T$ significance: $S_{E_{miss}^T} = \frac{E_{miss}^T}{(0.5 \sqrt{\text{GeV}}) \sqrt{\sum E_T}} > 6.0$
• veto events with leptons with $p_T > 15$ GeV
• data-driven QCD estimate: scaling events failing $S_{ETmiss}$ cut by efficiency measured in inverted ID sample

$W \rightarrow \tau \nu$ - Result

$$\sigma(W \rightarrow \tau \nu) = 11.1 \pm 0.3\, \text{(stat.)} \pm 1.7\, \text{(sys.)} \pm 0.4\, \text{(lumi.)\, nb}$$

$$\sigma_{\text{theory}} = 10.46 \pm 0.52\, \text{nb at NNLO}$$

Systematics:
- $\tau_h$ efficiency 10.3%
- $\tau_h$ energy scale 8.0%
- $\tau_h + \text{MET trigger}$ efficiency 7.0%
- luminosity 3.4%
- acceptance 2.3%

2010 data: Measurement with $W \rightarrow \tau \nu$
Tag & Probe Method, using $E_{\text{miss}}^{\tau}$ significance as tag
Excellent agreement between MC and data efficiencies

2011 data: Towards measurement with $Z \rightarrow \tau \tau$
Tag & Probe Method, using $\tau \rightarrow \mu \nu$ as tag.
Very good agreement between MC and data


[2] ATLAS: Tau Public Results
Search for Neutral Higgs Boson Decays to $\tau\tau$

Search for Higgs $\rightarrow \tau\tau$ in 1.06 fb$^{-1}$ of 2011 data
- With current statistics, mainly interesting for minimal SuperSymmetric model, MSSM

MSSM Higgs sector
- 5 bosons $h/H/A, H^+, H^-$
- Higgs sector determined by two parameters at tree level: $\tan\beta$ and $m_A$

Major production modes
- $h/H/A$: gg-fusion, $b$-associated

Dominant decay mode for large regions of MSSM parameter space (large $\tan\beta$)
- $h/H/A \rightarrow \tau\tau$
# Higgs $\rightarrow \tau \tau$ - Search Modes

## 4 decay modes investigated

### 1. $Higgs \rightarrow \tau \tau \rightarrow e\mu 4\nu$

- BR = 6%

**Event Selection:**
- Lepton trigger
- $p^e_T > 20$ GeV (22 if triggered)
- $p^{\mu}_T > 10$ GeV (20 if triggered)
- Opposite charge
- $p^e_T + p^{\mu}_T + E_T^{miss} < 120$ GeV
- $\Delta \phi(e,\mu) > 2$ rad

### 2. $Higgs \rightarrow \tau \tau \rightarrow e/\mu + T h 3\nu$

- BR = 23% + 23%

**Event Selection:**
- Lepton trigger
- 1 isolated lepton: $p^e_T > 25$ or $p^{\mu}_T > 20$ GeV
- 1 tau: $p^{Th}_T > 20$ GeV
- Opposite charge
- $E_T^{miss} > 20$ GeV
- $m_T = \sqrt{2p^e_T E_T^{miss}(1-\cos\Delta \phi)} < 30$ GeV
- No other lepton

### 3. $Higgs \rightarrow \tau \tau \rightarrow T h T h 2\nu$

- BR = 42%

**Event Selection:**
- Tau-pair trigger
- $p^{h,1}_T > 45$ & $p^{h,2}_T > 30$ GeV
- Opposite charge
- $E_T^{miss} > 25$ GeV
- Lepton veto
Validation of $Z \rightarrow \tau\tau$ shape

- Select $Z \rightarrow \mu\mu$ in data; replace $\mu$ response with $\tau$ response from simulation
- Apply event selection to “embedded” events
- Data agrees well with $Z \rightarrow \tau\tau$ simulation

QCD multijets

- Data-driven via “ABCD methods”:
  - $e\mu$ mode: SS/OS & lepton isolation
  - $T_hT_h$ mode: SS/OS & tau ID severity

Backgrounds in $T_h\ell\ell$ mode

- Background estimated by
  \[ n_{Bkg}^{OS} = n_{Bkg}^{SS} + n_{W}^{OS-SS} + n_{Z}^{OS-SS} + n_{other}^{OS-SS} \]
  - Assumed that QCD is SS/OS symmetric
  - validated on data control sample
  - Non-symmetric contributions estimated
  - $W$ ($n_{W}^{OS-SS}$): from data control sample
  - $Z$ ($n_{Z}^{OS-SS}$): from embedding technique
  - other processes ($n_{other}^{OS-SS}$): simulation

Higgs $\rightarrow \tau\tau$ - Mass Distributions (i)

Effective mass: invariant mass of triplet of $e$, $\mu$, and $p^{\text{miss}}_T$

$\sqrt{s} = 7$ TeV, $\int Ldt = 1.06$ fb$^{-1}$

ATLAS Preliminary

Higgs → ττ - Mass Distributions (ii)

\[ \sqrt{s} = 7\text{TeV}, \int L = 1.06\ \text{fb}^{-1} \]

**ATLAS Preliminary**

**MCC mass:** From

*Missing Mass Calculator*

[arXiv:1012.4686]

Visible mass: invariant mass of pair of visible decay products $\tau_{h,1}$ and $\tau_{h,2}$

$\sqrt{s} = 7$ TeV, $\int L dt = 1.06$ fb$^{-1}$

ATLAS Preliminary

No significant excess over Standard Model prediction observed.

Define 95% CL exclusion limits for generic Higgs production and decay $\sigma \times \text{BR}(\phi \rightarrow \tau \tau)$ as function of $m_\phi$.

Higgs → ττ - Results in MSSM Model

Interpret exclusion limits as exclusions in MSSM parameter space of $m_A$ and $\tan\beta$

\[
\begin{align*}
\text{All channels} & \\
\text{Observed CLs} & \\
\text{Expected CLs} & \\
\pm 1\sigma & \\
\pm 2\sigma & \\
\text{LEP} & \\
\text{ATLAS 36 pb}^{-1} \text{ observed} & \\
\text{ATLAS 36 pb}^{-1} \text{ expected} & \\
\end{align*}
\]

$\sqrt{s} = 7 \text{ TeV, } \int L dt = 1.06 \text{ fb}^{-1}$

Summary

- Tau leptons are interesting signatures at the LHC
  - especially for new phenomena with strong coupling to third generation and/or mass (Higgs)
- Excellent detector performance enables high performance tau ID
- LHC is performing excellently:
  - In 2010: $30-40 \text{ pb}^{-1}$
  - In 2011 (so far): $> 2 \text{ fb}^{-1}$
- Measurement of $W \rightarrow \tau \nu$ and $Z \rightarrow \tau \tau$ cross sections
  - Overall accuracies of 20% and 10%, respectively
  - Good agreement with NNLO predictions
- Search for Higgs decay to $\tau \tau$ in $e\mu$, $eT_h$, $\mu T_h$, and $T_h T_h$ final states
  - No evidence of Higgs boson observed; Exclusions limits derived.
- Data arriving rapidly: $\tau \tau$ channel getting interesting also for SM Higgs search.
References


[2] ATLAS Experiment - Tau Public Results
   https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TauPublicCollisionResults

[3] ATLAS Data Summary
   https://twiki.cern.ch/twiki/bin/view/AtlasPublic/EventDisplayPublicResults


[7] ATLAS Collaboration, Search for Neutral MSSM Bosons decaying to $\tau^+ \tau^-$ pairs in proton collisions at $\sqrt{s} = 7$ TeV with the ATLAS, ATLAS-CONF-2011-132
Backup Material
Higgs $\rightarrow \tau\tau$ - Some validation Plots

**eμ channel**

**eT_{h} + μT_{h} channels**

**T_{h}T_{h} channel**

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**ATLAS Preliminary**

\[
\sqrt{s} = 7\text{ TeV}, \int L = 1.06 \text{ fb}^{-1}
\]
Higgs → ττ - Results in MSSM Model

Interpret exclusion limits as exclusions in MSSM parameter space of $m_A$ and $\tan\beta$
Tag & Probe method, using $E_{\text{miss}}^T$ significance to tag events

The $N_{\text{trk}}$ spectrum of tau leptons vs. jets fit to extract the $W \rightarrow \tau \nu$ fraction

Multi-jet $N_{\text{trk}}$ spectrum taken from low $E_{\text{miss}}^T$ significance control region

Excellent agreement of data with MC efficiencies

Cross-checked with cross section normalization method, normalizing $W \rightarrow \tau \nu$ to measured $W$ cross-section in leptonic channels
Summary of Efficiency Results

**ATLAS** Preliminary

$\mathbf{L} = 34 \text{ pb}^{-1}$

**Tighter identification working point**

- **Cuts** *(Tag&Probe)*
  - 0.98 ± 0.11(stat) ± 0.10(sys)

- **Likelihood** *(Tag&Probe)*
  - 0.95 ± 0.09(stat) ± 0.05(sys)

- **Boosted decision trees** *(Tag&Probe)*
  - 0.92 ± 0.07(stat) ± 0.05(sys)

- **Cuts** *(Cross section)*
  - 0.96 ± 0.05(stat) ± 0.14(sys)

- **Likelihood** *(Cross section)*
  - 1.00 ± 0.07(stat) ± 0.13(sys)

- **Boosted decision trees** *(Cross section)*
  - 0.89 ± 0.05(stat) ± 0.10(sys)

**30-35% efficiency point**

- Measured efficiencies consistent with Monte Carlo $W \rightarrow \tau\nu$ events

- Tag & Probe method limited by background statistics in control region for multi-jet $N_{\text{trk}}$ spectrum

- Cross section normalization method limited by systematic uncertainties on signal acceptance

Scale Factor = $\varepsilon(\text{data})/\varepsilon(\text{MC})$
Tag & Probe method to derive tau efficiency:
Using 730 nb$^{-1}$, tau identification efficiency studied in $Z\rightarrow\tau\tau$ events where one tau decays via $\tau\rightarrow\mu\nu\nu$ (tag), and the other decays hadronically (probe)

Very good agreement between MC and data
(distribution of visible mass of muon-tau candidate shown)
The Large Hadron Collider

- 27 km circumference
- pp collisions at $\sqrt{s} = 7$ TeV
- instantaneous luminosity $10^{30} - 2\times10^{33}$ cm$^{-2}$s$^{-1}$
- 50–150 ns bunch spacing