Search for a Lepton Flavor Violating Higgs Boson Using the Compact Muon Solenoid Detector at the Large Hadron Collider

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Outline

- Theoretical Background
  - Standard Model
  - Higgs Boson
  - Lepton Flavor Violation
  - Signal and Backgrounds
- Experimental Background
  - Large Hadron Collider (LHC)
  - Compact Muon Solenoid (CMS)
- Analysis
  - Monte Carlo Generation
  - Selections
  - Results
  - Outlook
Standard Model (Particles)

- Theoretical framework that describes particle interactions

- Quarks
  - Six quarks in three generations
  - Quarks form hadrons (ex: proton, neutron)

- Leptons
  - Three generations
  - Each charged lepton has a neutrino partner

- Gauge Bosons
  - Force carriers

- Higgs Boson
  - Responsible for masses of quarks, leptons, and massive gauge bosons
Standard Model (Forces)

- **Strong Nuclear Force**
  - Mediated by gluon
  - Binds quarks within hadrons

- **Weak Nuclear Force**
  - Mediated by W and Z bosons
  - Responsible for beta decay of the neutron

- **Electromagnetic Force**
  - Mediated by photon
Massive Gauge Bosons

- Weak interaction has very short range
  - $10^{-17}$ m
- Requires massive mediators
  - W and Z bosons
- Weak interaction and electromagnetic interaction can be combined into Electroweak Lagrangian
  - Contains triplet of weak isospin currents with SU(2) symmetry and single hypercharge current with U(1) symmetry
  - W and Z mass terms of the form $M^2 W^\mu W_\mu$ are not SU(2) X U(1) gauge invariant
Standard Model Higgs Boson (Theory)

- **Higgs Mechanism**
  - Higgs field produces spontaneous symmetry breaking of Lagrangian in weak isospin x hypercharge space
  - Gauge transformation generates mass terms in Lagrangian for quarks, leptons, and massive bosons
  - SM Higgs has no charge, no spin, and is its own antiparticle

- **Discovery**
  - Discovery of Higgs Boson with a mass of 125-126 GeV announced on July 4th 2012
SM Higgs Boson (Major Production Mechanisms)

- **Gluon Gluon fusion**
  - Dominant at LHC
  - Higgs couples to virtual top quarks in loop
  - More than 10 times more likely than any other production mechanism

- **Vector boson fusion**
  - Second largest at LHC
  - Quarks in proton exchange virtual W or Z Boson
  - Higgs couples to virtual bosons

Source: Handbook of LHC Higgs Cross Sections: 3. Higgs Properties
Lepton Flavor Violation

• Lepton Number
  – 3 generations of leptons
  – Lepton number defined for each generation
    • #(leptons) - #(anti leptons)
  – Conserved in SM

\[
\begin{pmatrix}
  \nu_e \\
  e \\
  \nu_\mu \\
  \mu \\
  \nu_\tau \\
  \tau
\end{pmatrix}
\]

Lepton Number

Higgs

\begin{align*}
\mu^+ & \rightarrow W^- \nu_\tau \\
\tau^- & \rightarrow W^- \nu_\tau
\end{align*}

Lepton # conserved

Lepton # Violated

Lepton flavor violating Higgs

– Some beyond the standard model (BSM) theories predict flavor violating Higgs boson

– Search for Higgs decaying directly to a tau and a muon

Aaron Levine
Lepton Flavor Violating Higgs Decay

- SM process: $H \rightarrow \tau_\mu \tau_h$
  - $\tau_h$ denotes a tau decaying hadronically (hadrons and a tau neutrino)
  - $\tau_\mu$ denotes a tau decaying to a muon (with a tau neutrino and an antimuon neutrino)
  - MET denotes missing energy
    - Neutrinos are not detected by CMS
    - $H \rightarrow \tau\tau$ Branching Ratio (BR) of 6.3 % at $M_H = 125$ GeV

- Similar BSM LFV process: $H \rightarrow \mu\tau_h$
  - No previous direct experimental searches
  - BR up to 13%
    - Based on analysis of ATLAS $H \rightarrow \tau\tau$ data by Harnik, Kopp, Zupan
  - Larger visible mass than SM process
  - Search Higgs Mass range of 125-126 GeV
  - Assume SM production modes
Important Backgrounds

- **Z+jets**
  \[ \sigma = 3500 \text{ pb} \]

- **ttbar**
  \[ \sigma = 130 \text{ pb} \]

- **W+jets**
  \[ \sigma = 38000 \text{ pb} \]

- **WW**
  \[ \sigma = 5.8 \text{ pb} \]

W decays hadronically or leptonically
Large Hadron Collider

- 14 TeV Center of Mass proton/proton collider
  - Currently operating at 8 TeV
- 27 km circumference
- Four experiments
  - CMS, ATLAS: General purpose high energy physics detector
  - LHCb: High energy B physics
  - ALICE: High energy heavy ion physics
LHC Collisions

- **Acceleration Process**
  - Electric field strips Hydrogen atoms of electrons
  - Linear accelerator accelerates protons to 50 MeV
  - Synchrotrons accelerate protons to 450 GeV
  - Protons then go to main LHC beam, accelerated to 4 TeV
- **Protons are guided by superconducting magnets cooled by liquid helium**
  - Dipoles accelerate protons
  - Quadrupoles focus protons along horizontal and vertical planes
- **RF system creates bunches of protons**
  - 25 ns design bunch spacing

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Energy (TeV)</td>
<td>7</td>
<td>3.5</td>
<td>3.5</td>
<td>4</td>
<td>6-7</td>
</tr>
<tr>
<td>Bunches/Beam</td>
<td>2835</td>
<td>368</td>
<td>1380</td>
<td>1380</td>
<td>2835</td>
</tr>
<tr>
<td>Protons/Bunch(1e11)</td>
<td>1.15</td>
<td>1.3</td>
<td>1.5</td>
<td>1.5</td>
<td>1.2</td>
</tr>
<tr>
<td>Peak Luminosity(1e32cm⁻²s⁻¹)</td>
<td>100</td>
<td>2</td>
<td>30</td>
<td>60</td>
<td>100</td>
</tr>
<tr>
<td>Integrated Luminosity (fb⁻¹)</td>
<td>100/year</td>
<td>.036</td>
<td>6</td>
<td>19.71</td>
<td>50/year</td>
</tr>
</tbody>
</table>

$$\mathcal{L} = \frac{\#\text{Interactions}}{\text{Effective Flux}}$$
Compact Muon Solenoid (CMS)

- General background
  - Located 100 meters underground in Cessy, France
  - One of two general physics detectors at the LHC
  - Size
    - 21 meters long
    - 15 meters wide
    - 12500 tons

- Physics Goals
  - Study Higgs Boson
  - Search for BSM (Beyond the Standard Model) physics
Pseudorapidity ($\eta$) is a Lorentz invariant quantity that describes the position of a particle relative to the beam axis.

$$\eta = -\ln(\tan(\theta/2))$$

$\theta = \text{angle relative to z axis}$

Transverse mass ($M_T$) and momentum ($P_T$) correspond to the mass and momentum of a particle perpendicular to the beam axis.
CMS Tracker

- Measures $P_T$ and charge of muons, electrons, and hadrons, using 3.8 T magnetic field
  - $P_T$ determined by examining tracker hits to reconstruct the radius of curvature
- Extends to $|\eta| < 2.5$
- Resolution: $\left( \frac{\delta P_T}{P_T} \right)^2 = (15 P_T(\text{TeV})\%)^2 + (0.5\%)^2$
- Inner silicon pixel detector
  - High granularity
  - Pixels are 100 X 150 μm
  - Cylindrical layers at 4, 7, and 11 cm from beam
  - High flux (10 million particles per square cm per second)
- Outer silicon strip detector
  - 10 cylindrical layers with 4 endcaps
  - Extends 130 cm from beam
  - Lower flux than pixel detector (3e5 particles per square cm per second)
    - Allows cell size up to 25 cm x 180 μm
CMS Electromagnetic Calorimeter

- Measures energy deposited by electrons and photons
- Composed of lead tungstate scintillating crystals
  - Crystals have high density (8.28 g/cm$^3$) and short radiation length (0.89 cm)
    - Allows fine granularity
  - 61,200 crystals in the barrel
  - 7324 crystals in each of the two endcaps
  - Emitted light detected by photodetectors
- 80% of light emitted in 25 ns
  - Same order as LHC design bunch crossing time
- Energy resolution: $\left( \frac{\sigma}{E} \right)^2 = \left( \frac{2.8\%}{\sqrt{E}} \right)^2 + \left( \frac{0.12}{E} \right)^2 + (0.30\%)^2$
CMS Hadronic Calorimeter

- Measures energy deposited by hadrons
- Barrel and Endcaps
  - Barrel (HB): $|\eta| < 1.3$
  - Endcaps (HE): $1.3 < |\eta| < 3.0$
  - Wedges of brass absorber and plastic scintillator
  - Wavelength shifting fibers bring scintillation light to electronics
  - Energy resolution: $(\frac{\sigma}{E})^2 = (\frac{115\%}{\sqrt{E}})^2 + (5.5\%)^2$
- Forward Calorimeter (HF)
  - $3.0 < |\eta| < 5.0$
  - Very high flux region
  - Quartz scintillating fibers
  - Steel shielding for electronics
  - Energy resolution: $(\frac{\sigma}{E})^2 = (\frac{280\%}{\sqrt{E}})^2 + (11\%)^2$
CMS Muon Chamber

- Muons are highly penetrating particles that are very important for new physics
  - Not stopped by Calorimeters
    - Need muon system
- Trajectory is bent by 2T magnetic field in return yoke
  - 4 muon stations interspersed with iron yoke
    - 610 resistive plate chambers
      - Redundant trigger system, provides time coordinate
    - 250 drift tubes track the muons in the barrel
      - Barrel covers $|\eta| < 1.2$ region
    - 500 cathode strip chambers (CSC) track the muons in the endcaps
      - Endcaps cover up to $|\eta| < 2.4$
    - Drift tubes and CSCs provide position of muon
      - Both use cathode strips and anode wires
      - Muons ionize gas, electrons drift to anode wires
CMS Trigger System

- Impossible to store all data produced via LHC collisions
- Trigger system must reduce rate from 1 GHz (LHC collisions) to 300 Hz (maximum output rate)
- Level 1 Trigger
  - High speed electronics
  - Basic selection and rejection
  - Rate limited by readout electronics
    - Tracker has 7 μs readout time, 8 event buffer
- High Level Trigger
  - Compute nodes
    - 20,000 cores
  - Defines object filters for physics analysis
CMS Level 1 Trigger

- Level 1 Trigger must analyze every bunch crossing
- Global trigger uses hardware algorithms to accept or reject each event it receives
- Calorimeter triggers sum energy over $\eta/\phi$ regions
  - 5X5 crystal block = trigger tower
- Regional Calorimeter Trigger (RCT)
  - Identify e/\gamma candidates
  - Sums transverse energy ($E_T$) in regions
- Global Calorimeter Trigger (GCT)
  - Jet identification
- Muon trigger system (RPC,DT,CSC)
  - Records energy and track geometry of muons
  - Global Muon Trigger combines information to determine well identified muon candidates
CMS Level 1 Trigger Upgrade

- Long Shutdown 1 (LS1) from 2013-2015
- Increase beam energy to 6-7 TeV
- Decrease bunch spacing from 50 ns to 25 ns
- Need to improve tau identification efficiency because taus couple strongly to Higgs boson
  - ID taus as taus, not as jets
- Example: change tau identification from 12X12 trigger towers to 2X1 ECAL+HCAL towers
  - Increases plateau efficiency from 0.3 to 0.7
  - Overall L1 Trigger rate remains below 100 kHz with upgrade algorithms

Source: Level-1 Trigger Upgrade Technical Design Report
CMS High Level Trigger

- Processes events from L1 trigger
- Uses offline software algorithms to define filters for physics analysis
- Accepts events at up to 100kHz, outputs events at up to 300 Hz
  - Large reduction in rate
- Example: HLT filter used for this analysis:
  - Requires isolated, well constructed muon with $P_T > 30$ GeV
  - The terms “isolated” and “well constructed” will be defined in future slides
Analysis Summary

• Simulation techniques
  – Monte Carlo (MC) techniques used to simulate signal and background
• Object Identification and Reconstruction
  – Muons
  – Jets
  – Taus
• Initial Data/Monte Carlo Comparison
• Analysis Selections
• Results and Future Plans
Monte Carlo Generators

- **Madgraph**
  - Matrix element MC generator
  - Partonic interactions

- **Pythia**
  - Quarks allowed to radiate gluons
  - Hadronization, showering

- **Tauola**
  - Simulates Tau decay
  - Used in conjunction with Pythia
  - Takes into account tau polarization and spin
Monte Carlo Workflow

- Generate samples with Madgraph + Tauola and Pythia
  - Partonic level to hadronization and tau decay
- Use GEANT to simulate detector interactions
  - Software for simulating passage of particles through matter
  - Currently responsible for most of signal simulation
    - New signal monte carlo studies are ongoing
- Use CMSSW software to reconstruct MC events to be compatible with CMS analysis framework
- Scale MC samples to 19.71 fb\(^{-1}\) of data
  - 8 TeV dataset used in this analysis
Muon Reconstruction

- **Standalone Muons**
  - Offline reconstructed track segments in muon chambers
- **Global Muons**
  - Match standalone muons to tracks in silicon tracker
  - Fit and reconstruct path
- **Tracker Muons**
  - ID low PT muons that don't register as standalone muons
  - Reconstruct track with $P > 2.5$ GeV, $P_T > 0.5$ GeV matched with hit in muon chamber
Muon Isolation

- Muon from LFV Higgs decay should be isolated
- Define isolation cone around muon
  - $\Delta R = \sqrt{\phi^2 + \eta^2} < 0.4$
- Relative Isolation Definition
  - Tracker isolation: sum of PT of tracks in isolation cone
  - ECAL isolation: sum of ECAL energy deposited in isolation cone
  - HCAL isolation: sum of HCAL energy deposited in isolation cone

$$ISO_{Rel} = \frac{ISO_{HCAL} + ISO_{ECAL} + ISO_{Tracker}}{\mu P_T} < 0.12$$
Particle Flow Objects

- Reconstruct hadrons, photons, muons, and electrons
  - Used to identify jets, taus, and missing $E_T$ (MET)
- Particle Flow Algorithms identify objects
  - Identify calorimeter clusters and tracker hits
  - Reconstruct path and identify particles
- Example:
  - Electron will have a curved path in tracker and will leave an energy deposit in ECAL
Jet Identification

• Particle flow jets
  – Reconstruct jets from energy deposited by particle flow objects
• Define distance measures $d_{ij}$ and $d_{iB}$
  – $d_{ij}$ = distance between particles i and j
  – $d_{iB}$ = distance between particle i and beam
  – If $d_{ij} < d_{iB}$ then combine particles i and j
  – If $d_{ij} > d_{iB}$ then call particle i a jet
• Use Anti-kt jet algorithm ($p = -1$) with $R = 0.5$
• Anti-kt algorithm keeps jet cone well defined
  – Cone unaffected by soft radiation
  – Hard events within cone are combined based on energy and position
  – Collinear and infrared safe
• Find cones by identifying clusters of HCAL depositions
Tau Reconstruction

Use hadronic tau decays for identification
- 64% branching ratio

- Three primary decay modes
  - Single prong (π)
  - Single prong plus strip (π and π⁰ or π⁰π⁰)
  - Three prong (π π π)

- Hadron Plus Strips (HPS) algorithm
  - Photons from π⁰ decay may convert to electrons in tracker
    - Trajectory of electrons is bent by magnetic field
    - Use “strips” in ECAL to reconstruct π⁰ candidates
  - π⁰ candidates matched to tau signatures in particle flow jets
  - π candidates matched to HCAL depositions
Preselection Strategy

- Apply loose “preselection” cuts before applying full analysis cuts
- Allows data/MC comparison
  - More statistics than signal region
  - Allows testing of analysis strategies before implementation in signal region
- “Blind” portion of preselection region
  - Hide data events where the signal is non-negligible to prevent biased selection
- Require well reconstructed Muon
  - $P_T > 30$ GeV
  - $|\eta| < 2.1$
- Require well reconstructed Tau
  - $P_T > 25$ GeV
  - $|\eta| < 2.3$
- Eliminate events irrelevant to signal
  - Require Muon and Tau to have opposite sign
- Separate events into 0, 1, and 2 jet channels
  - 0 and 1 jet events correspond to gluon gluon fusion
  - 2 jet events correspond to VBF
Data approximately matches MC models

0 Jet

<table>
<thead>
<tr>
<th>Events: (80-140 GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal: 1700</td>
</tr>
<tr>
<td>Background: 26000</td>
</tr>
<tr>
<td>Signal/Background: 0.07</td>
</tr>
</tbody>
</table>
H→μτ_h 1 Jet Backgrounds

- Backgrounds are determined in the same way as the 0 jet backgrounds.
- Data approximately matches MC models within statistical uncertainty.

<table>
<thead>
<tr>
<th>1 Jet</th>
<th>Events:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(80-140 GeV)</td>
</tr>
<tr>
<td>Signal:</td>
<td>820</td>
</tr>
<tr>
<td>Background:</td>
<td>13000</td>
</tr>
<tr>
<td>Signal/Background</td>
<td>0.07</td>
</tr>
</tbody>
</table>
H→μτₜₜ VBF (2 Jet) Backgrounds

\[ \sqrt{s} = 8 \text{ TeV} \quad L = 19.71 \text{ fb}^{-1} \]

**Fakes:** Includes QCD, W+jets
Determined by Fake Rate Method

Data/MC agreement suggests that systematic uncertainties should be increased. Studies are ongoing.

**TT+Jets:** Normalization and shape from Monte Carlo

**WW:** Normalization and Shape from Monte Carlo

MC and Fake rate statistical uncertainty

**Z⁻→ττ:** (embedded data samples for shape, DY + (1,2,3,4) jet samples for normalization

<table>
<thead>
<tr>
<th>2 Jet</th>
<th>Events: (70-120 GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal:</td>
<td>290</td>
</tr>
<tr>
<td>Background:</td>
<td>1600</td>
</tr>
<tr>
<td>Signal/Background</td>
<td>0.19</td>
</tr>
</tbody>
</table>
W+Jets and QCD Estimation Techniques

- Get W+jets shape from Monte Carlo
- Compute the appropriate normalization factor by scaling W+jets in region dominated by W+jets
  - \( M_T(\tau, \text{MET}) > 70 \text{ GeV} \)
  - Require \((W+jets \text{ events}) = (\text{data events} - \text{other background events})\)
  - Scale factor of 0.8 for 0 Jet
  - Scale factor of 1.0 for 1 Jet

- Determine QCD shape by inverting muon isolation in the data sample
  - Invert isolation to enter rich realm of QCD statistics
  - Compute normalization factor by requiring QCD to agree with data in same sign region
    - Same sign: muon and tau have same sign
    - High QCD statistics in this region
W+Jets Estimation Results

0 Jets, Preselection
Scaled for $M_T(\tau, \text{MET}) > 70$ GeV

No $M_T(\tau, \text{MET}) < 10$ cut
Check scaling close to signal region
H→μτ_h VBF Fakes Estimation

• The fake rate method is a way of improving W+jets and QCD background estimation in the 2 jet channel
• Select events with two muons and a tau
  – fake tau rich region
• Estimate tau fake rate (fTau) by computing the fraction of events that are identified as taus but are not isolated
• Invert tau isolation in data sample to enter rich region of tau fakes
• Weight events by a factor of fTau/(1-fTau)
  – Gives shape and yield of “fake” tau events
  – This group of events is dominated by W+jets and QCD

\sqrt{s} = 8 \text{ TeV} \quad L = 19.71 \text{ fb}^{-1}
VBF Fake Rate Validation

\[ \sqrt{s} = 8 \text{ TeV} \quad L = 19.71 \text{ fb}^{-1} \]

- Compare W+jets Monte Carlo and data driven QCD to fake rate method in fakes control region
  - Preselection cuts
  - Muon and tau have same sign
  - \( M_T(\mu,\text{MET}) > 70 \text{ GeV} \)
- Data/MC agreement within uncertainties

Calculate uncertainty in fake rate by shifting fake rate up and down by error bars from data (previous slide).
Z→ττ Estimation

- Low Z+jets MC statistics
  - Estimate shape from Z→ττ embedded samples
  - Normalization from Drell Yan + (1,2,3,4) Jet MC
    - Drell Yan: quark/anti-quark annihilation that produces Z boson
- Z+jets(other) negligible in VBF channel

- Examine method in VBF Z→ττ control region
  - Preselection Cuts
    - ΔR(μ,τ) < 2.0

Embedded Method

\[
\sqrt{s} = 8 \text{ TeV} \quad L = 19.71 \text{ fb}^{-1}
\]
**H→μτ_h Signal Region Cuts:**

**Gluon Gluon Fusion (GGF)**

- Selection optimized in 0 Jet GGF category by varying cuts to maximize \( \frac{signal}{\sqrt{background}} \)

**0-Jet Category:**
- Preselection
- 0 Jets \((p_T > 30 \text{ GeV})\)
- \(p_T(\mu) > 40 \text{ GeV}\)
- \(p_T(\tau) > 25 \text{ GeV}\)
- \(\Delta\Phi(\mu,\text{MET}) > 2.5\)
- \(\Delta\Phi(\tau,\text{MET}) < 0.3\)
- \(M_T(\tau,\text{MET}) < 10 \text{ GeV}\)

**1-Jet Category:**
- Preselection
- 1 Jet \((p_T > 30 \text{ GeV})\)
- \(p_T(\mu) > 40 \text{ GeV}\)
- \(\Delta\Phi(\tau,\text{MET}) < 0.3\)
- \(p_T(\tau) > 25 \text{ GeV}\)
- \(M_T(\tau,\text{MET}) < 10 \text{ GeV}\)

**Sensitive to GGF**

LFV Higgs process has low \(M_T(\tau,\text{MET})\) and \(\Delta\Phi(\tau,\text{MET})\) because the emitted tau and neutrino are roughly collinear
Signal Region: $H \rightarrow \mu \tau \_h$ 0 and 1 Jet Channels

**0 Jets**

- Events: (80-140 GeV)
  - Signal: 620
  - Background: 1100
  - Signal/Background: 0.55

**1 Jet**

- Events: (70-140 GeV)
  - Signal: 290
  - Background: 890
  - Signal/Background: 0.33

S/B increase by factor of 7.9 from preselection

S/B increase by factor of 4.7 from preselection
$H \rightarrow \mu \tau_h$ Signal Region Cuts: Vector Boson Fusion (VBF)

- Selection optimized by varying cuts to maximize \[ \frac{\text{signal}}{\sqrt{\text{background}}} \]

**2-Jet Category:**

Preselection
- 2 Jets ($p_T > 30$ GeV)
- $M_{jj} > 600$ GeV
- $|\Delta\eta(jj)| > 3.5$
- $p_T(\mu) > 45$ GeV
- $p_T(\tau) > 45$ GeV
- $M_T(\tau, \text{MET}) < 30$ GeV
- Central jet veto (30 GeV)

Sensitive to VBF

Central jet veto reduces $t\bar{t}$bar and QCD

VBF jets have pronounced separation in $\eta$

Heavy $t$ quark may radiate gluons which produce hadronic showers (central jets)

Central jet veto eliminates jets with $P_T > 30$ GeV that are not either of the 2 leading jets
Signal Region: $H \rightarrow \tau_h \mu$ 2 Jet Channel

$\sqrt{s} = 8$ TeV  $L = 19.71$ fb$^{-1}$

<table>
<thead>
<tr>
<th>2 Jets</th>
<th>Events:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal</td>
<td>21</td>
</tr>
<tr>
<td>Background</td>
<td>3.9</td>
</tr>
<tr>
<td>Signal/Background</td>
<td>5.4</td>
</tr>
</tbody>
</table>

Recall: S/B = 0.19 for Preselection Cuts
Improvement by factor of 28
## Systematic Uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Common (Signal+Background)</td>
<td></td>
</tr>
<tr>
<td>Luminosity</td>
<td>2.6%</td>
</tr>
<tr>
<td>Trigger</td>
<td>1-3%</td>
</tr>
<tr>
<td>Muon Trigger/ID/Isolation</td>
<td>2%</td>
</tr>
<tr>
<td>Tau ID/Isolation</td>
<td>6%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Backgrounds</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Z → ττ Embedding</td>
<td>3%</td>
</tr>
<tr>
<td>WJets/QCD</td>
<td>20%</td>
</tr>
<tr>
<td>Tau Fakes</td>
<td>30%</td>
</tr>
<tr>
<td>WW+Jets (MC NLO)</td>
<td>15%</td>
</tr>
<tr>
<td>TTBar+Jets</td>
<td>10%</td>
</tr>
<tr>
<td>SingleTop</td>
<td>10%</td>
</tr>
<tr>
<td>SM Higgs</td>
<td>10%</td>
</tr>
</tbody>
</table>

- Small luminosity and trigger uncertainties are standard CMS values
- Object ID and Isolation uncertainties are from the respective particle object groups
- Tau fake uncertainty
  - Shift fake yield up and down by uncertainty on Z→μμ data
  - \( \frac{(Yield_{\text{up}} - Yield) / Yield}{Yield} = \frac{Yield - Yield_{\text{down}}}{Yield} = 30\% \)
- MC Backgrounds: estimate of 10-15% uncertainty on MC
- Systematic uncertainties used for the expected limit calculations
### Sensitivity to Exclusion Limits

All numbers given are expected limits on branching ratio (BR) \((H \rightarrow \tau_h \mu)\)

#### 95% Confidence Level (Blinded Analysis)

<table>
<thead>
<tr>
<th></th>
<th>0 Jets</th>
<th>1 Jet</th>
<th>2 Jets</th>
<th>All</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\tau_{\text{had}} \mu)</td>
<td>BR: 1.69 +/- 0.86%</td>
<td>BR: 2.50 +/- 1.29% (not optimized)</td>
<td>BR: 2.12 +/- 1.08%</td>
<td>BR: 1.12 +/- 0.57%</td>
</tr>
</tbody>
</table>

**Expected Limit:** Limit that can be established after unblinding if signal is not detected.

**Definition of 95% confidence level limit:**

\[
\text{Probability}[\text{BR}(H \rightarrow \mu \tau_h) < 1.12\%] \geq 95%
\]

These limits are computed using the standard confidence level estimation procedure for CMS and ATLAS.
Future Plans

- Pre-upgrade analysis goals
  - Repeat limits with new signal MC
    - Pileup and tau decay with tauola
  - Add jet energy scale and tau systematics
  - Unblind analysis and compute BR($H \rightarrow \mu \tau$)
    - Will verify or put new constraints on BSM theories
- Planned LHC upgrade for 2015
  - Beam energy of 6-7 TeV
  - Gluon gluon Higgs production cross section will increase to 50 pb (at 14 TeV)
    - Increase by factor of 2.6
  - VBF cross section will increase to 4.2 pb (at 14 TeV)
    - Increase by factor of 2.7
  - Cross sections of major backgrounds expected to increase by factor of 2
  - Expected limit will improve by about a factor of 3
  - Expect 50 fb$^{-1}$ of new data in first year of upgrade to use for my thesis
Conclusions

- This analysis is currently sensitive to an expected limit of 1.12% +/- 0.57% for BR(H→μτ)
  - Improved sensitivity to come with LHC upgrade
- This analysis is well equipped to search for the BSM H→μτh process
- This is the first analysis to make a direct search for a Lepton Flavor violating Higgs boson