Rare/Exotic Decays of the Higgs Boson

K.K. Gan
The Ohio State University

On behalf of ATLAS and CMS

January 8, 2016
Outline

- Introduction
- Search for $H \rightarrow e\mu$
- Search for $H \rightarrow e\tau$
- Search for $H \rightarrow \mu\tau$
- Search for Higgs decays into new light bosons
- Search for invisible Higgs decays
- Summary
Why Search for Rare/Exotic Decays?

- Discovery of Higgs in 2012 is a crowning achievement of SM
  - SM is simple/elegant but incomplete...
    - why three generations of elementary particles?
    - masses/couplings are free parameters
    - why neutrinos are left-handed?
    - what is the dark matter?
  ⇐ search for new physics in rare/exotic decays of Higgs
    - rare decays might be more sensitive to new physics contribution
    - exotic decays would be a clear sign of physics beyond SM
Search for Lepton Flavor Violation

- Lepton flavor conservation is an assumption of SM
- No known symmetry associated with lepton flavor conservation
- Observation of LFV would revolutionize our understanding of particles and fields
  - Require a $7\sigma$ signal to claim a discovery?
    - Louis Lyons suggested requiring $7\sigma$ for SUSY discovery
- Discovery of muon 80 years ago started the LFV search industry
  - "Best" limit: $B(\mu \rightarrow e\gamma) < 5.7 \times 10^{-13} \text{ @ } 90\%\text{CL}$
    - $B(H \rightarrow e\mu) < O(10^{-8})$
  - Much less constrained for decays involving $\tau$ leptons
    - $B(H \rightarrow e\tau/\mu\tau) < O(10\%)$
    - Promising venue for discovery
CMS Search for $H \rightarrow \ell^+\ell^-$

- $\ell^+$ and $\ell^-$ have opposite charge
- $P_T(\text{lepton}) > 20-25$ GeV
- missing $E_T < 20-30$ GeV
- enhance sensitivity to different production processes (VBF, ggF, W/ZH) with different selection criteria for 0, 1, 2 jets
- no significant excess of events
  \( B(H \rightarrow \ell^+\ell^-) < 0.036\% @ 95\% \text{ CL} \)

CMS-PAS-HIG-14-040

![CMS-PAS-HIG-14-040](image_url)
● direct limits on couplings are less stringent than indirect limits but require no theoretical assumptions

\[ Y_{e\mu} Y_{\mu e} < \frac{m_e m_\mu}{v^2} \]
CMS Search for $H \rightarrow e\tau$

- Search for $H \rightarrow e + (\mu \text{ or } h^\pm + \leq 2\pi^0 \text{ or } h^\pm h^+ h^-)$
- $H \rightarrow e + \mu$:  
  - one isolated $e$ + one isolated $\mu$ of opposite charge
- $H \rightarrow e + \text{hadrons}$:
  - one isolated $e$ + one isolated hadronic $\tau$ decay of opposite charge
- enhance sensitivity to different production processes (VBF, ggF, W/ZH) with different selection criteria for 0, 1, 2 jets
- Use collinear mass ($M_{\text{collinear}}$) as an estimator of the Higgs mass to discriminate against background
  - use visible $\tau$ decay products to approximate $\nu$ direction
Limits on Lepton-Flavor-Violating Couplings

- No significant excess of events with $100 < M_{\text{collinear}} < 150$ GeV
- $B(H \rightarrow e\tau) < 0.70\%$ @ 95% CL

$\Rightarrow$ most stringent direct limits on lepton-flavor-violating couplings

- $\tau \rightarrow 3e$
- $\tau \rightarrow e\gamma$
- $H \rightarrow e\tau$

Theoretical interpretation of ATLAS result

Naturalness limit

K.K. Gan
ATLAS Search for $H \rightarrow \mu \tau$

- Search for $H \rightarrow \mu + (1 \text{ or } 3 \text{ hadrons}) + \text{ missing transverse energy ($E_T$)}$
  - $\mu$ and $\tau_{\text{had}}$ have opposite charge
  - $P_T(\mu) > 26 \text{ GeV}$
  - $P_T(\tau_{\text{had}}) > 45 \text{ GeV}$
  - $|\eta(\mu) - \eta(\tau_{\text{had}})| < 2$
- high detection efficiency: 99%
- effective in rejecting $W + \text{jets}$ and multi-jet background

K.K. 6
Results of Two Search Regions

**SR1**
- Lower efficiency
- Higher background

**SR2**
- Lower efficiency
- Higher background
Result of Combined Search Regions

- Data is consistent with background to within $1.3\sigma$
- $B(H \rightarrow \mu\tau) < 1.85\%$ @ 95%CL
  - expected limit: 1.24%
CMS Search for H → \( \mu \tau \)

- Search for H → \( \mu + (e \text{ or } h^\pm + \leq 2\pi^0 \text{ or } h^\pm h^+ h^-) \)
- H → \( \mu + e \):
  - one isolated \( \mu \) + one isolated \( e \) of opposite charge
  - main background: \( Z \rightarrow \tau\tau \)
- H → \( \mu \) + hadrons:
  - one isolated \( \mu \) + one isolated hadronic \( \tau \) decay of opposite charge
  - main background: misidentified \( \tau \) in \( W + \) jets, multiple jets, \( t \)-pairs
- enhance sensitivity to different production processes (VBF, ggF, W/ZH) with different selection criteria for 0, 1, 2 jets
- Use collinear mass (\( M_{\text{collinear}} \)) as an estimator of the Higgs mass to discriminate against background
  - use visible \( \tau \) decay products to approximate \( \nu \) direction
CMS Search for $H \rightarrow \mu \tau$

- Mass spectrum has excess of events in one bin near 125 GeV
- consistency with background only is $2.4\sigma$ ($p$-value = 1%)

K.K. Gan

ZPW2016 13
Limits on Lepton-Flavor-Violating Couplings

- \( B(H \to \mu \tau) < 1.51\% @ 95\% \text{ CL} \)

\[ \tau \to 3\mu \]

ATLAS: \( B < 1.85\% \)

\( \Rightarrow \) most stringent direct limits on lepton-flavor-violating couplings

- Theoretical interpretation of ATLAS result

- \( \tau \to \mu \gamma \)

- \( H \to \mu \tau \)

- Naturalness limit

Some extensions to SM contain dark or hidden sector

- provide dark vector boson $Z_d$ that could be dark matter candidate

Exotic decay $H \rightarrow 4l$ can be produced via two processes:

- $H \rightarrow ZZ_d \rightarrow 4l$
  - rate depends on the kinetic or mass mixing between $Z_d$ and $Z$

- $H \rightarrow Z_dZ_d \rightarrow 4l$
  - rate depends on the coupling between $Z_d$ and $H$

- distinctive $4l$ signature is readily detectable for $m(Z_d) > 15$ GeV
Search for $H \rightarrow ZZ_d \rightarrow 4l$

- Search for narrow resonance ($m_{34}$) recoiling against a $Z$ boson
  - no evidence of an enhancement
  - set upper limit on $B(H \rightarrow ZZ_d \rightarrow 4l)$
  - can be translated into upper limits on the kinetic or mass mixing between $Z_d$ and $Z$
Search for $H \rightarrow Z_d Z_d \rightarrow 4l$

- Search for enhancement in distribution of minimum $\Delta m = |m_{12} - m_{34}|$
  - no evidence of a signal
  - set upper limit on $B(H \rightarrow Z_d Z_d \rightarrow 4l)$
  - can be translated into upper limit on coupling between $Z_d$ and $H$
CMS Search for Higgs Decays into New Light Bosons

- Some extensions of SM contain extended Higgs sectors
  - Higgs can decay into a pair of light scalars or pseudo-scalars:
    \[ H \rightarrow hh \rightarrow 4\tau \text{ or } H \rightarrow aa \rightarrow 4\tau \]

- Higgs production processes used:
  - gluon fusion
  - vector boson fusion
  - vector boson associated production

- Event signature:
  - one isolated high \( P_T \) muon to trigger the event
  - relative low mass \( h \) or \( a \) resulted in highly boosted pair of \( \tau \)'s
    - \( \tau \)'s are not very isolated
    - require at least one highly boosted pair of \( \tau \)'s
    - one \( \tau \) must decay into a muon
Search for Higgs Decays into New Light Bosons

- Divide the search region into low and high $M_T$ regions
  - high $M_T$ region has enhanced contribution from $W$ associated production
- Search for excess of events with high visible tau-pair mass:
  $m_{\mu+X} > 4$ GeV
  - no excess of events observed
Search for Higgs Decays into New Light Bosons

- $B(H \to aa \to 4\tau) < 50\%$ for $m_a > 7$ GeV at 95\% CL
- $B < 21\%$ for $m_a = 9$ GeV

K.K. Gan

ZPW2016
ATLAS Search for Invisible Decays

- Higgs can decay into “invisible” final state:
  - $B(H \rightarrow ZZ \rightarrow 4\nu) \sim 0.1\%$

- Higgs might decay into dark matter or weakly interacting long-lived/stable particles

- Invisible decays of Higgs must be tagged:
  - large missing transverse energy
  - tag with leptons or jets

- Search in two production mechanisms:
  - vector boson fusion
    - two jets with large separation in $\eta$
    - best sensitivity
  - vector boson associated production
ATLAS Search for Invisible Decays

<table>
<thead>
<tr>
<th>Channel</th>
<th>Observed (%)</th>
<th>Expected (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VBF</td>
<td>28</td>
<td>31</td>
</tr>
<tr>
<td>$Z(ll)H$</td>
<td>75</td>
<td>62</td>
</tr>
<tr>
<td>$W/Z(jj)H$</td>
<td>78</td>
<td>86</td>
</tr>
<tr>
<td>Combined</td>
<td>25</td>
<td>27</td>
</tr>
</tbody>
</table>

- $B < 25\%$ @ 95\% CL for invisible Higgs decays
- $B < 23\%$ if visible Higgs decays are included
  - more model independent
    - no assumption that vector boson couplings $\leq$ SM couplings

JHEP11(2015)206
CMS Search for Invisible Decays

- **Vector boson fusion (VBF):**
  - large cross section
  - two jets plus large missing $E_T$
  - large background

- **Gluon fusion:**
  - 10 x larger cross section than VBF
  - search for mono-jet

- **vector boson associated production:**
  - small cross section
  - tag with vector boson that decays into jets, lepton or $b$-pairs
CMS Search for Invisible Decays

<table>
<thead>
<tr>
<th>Channel</th>
<th>Observed (%)</th>
<th>Expected (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VBF</td>
<td>57</td>
<td>40</td>
</tr>
<tr>
<td>VH</td>
<td>60</td>
<td>69</td>
</tr>
<tr>
<td>ggH</td>
<td>67</td>
<td>71</td>
</tr>
<tr>
<td>Combined</td>
<td>36</td>
<td>30</td>
</tr>
</tbody>
</table>

- No significant excess of events above SM backgrounds
  - Set upper limit on cross section normalized to SM cross section
    - < 36% @ 95% CL for invisible Higgs decays
CMS Search for Invisible Decays

- Search for Higgs decays into invisible particles and photons:
  \[ m_{\tilde{\chi}_1^0} > \frac{1}{2} m_H : H \rightarrow \tilde{\chi}_1^0 \tilde{G} \rightarrow \gamma \tilde{G} \tilde{G} \]
  \[ m_{\tilde{\chi}_1^0} < \frac{1}{2} m_H : H \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow \gamma \tilde{G} \gamma \tilde{G} \]

- Use Higgs produced in two mechanisms:
Search for Invisible Decays

- $ggH$ has no sensitivity below $m_H/2$ due to missing $E_T$ and photon $P_T$ requirements
- Upper limit on branching fraction is $\sim 10\%$ @ 95% CL

K.K. Gan

Summary

- No evidence for lepton-flavor-violating Higgs decays:
  - $B(H \rightarrow e\mu) < 0.036\%$
  - $B(H \rightarrow e\tau) < 0.70\%$
  - $B(H \rightarrow \mu\tau) < 1.51\%$

- No evidence for Higgs decays into new light bosons
  - presented here only two of the several searches by ATLAS/CMS

- No evidence for invisible Higgs decays: $B < 23\%$

- Results mostly based on $\sim 20$ fb$^{-1}$ at 8 TeV

- Will reach new level of sensitivity to new physics at 13 TeV
  - cross section increases by 2.3x
  - expected to collect 100 fb$^{-1}$ in three years
CMS paper on $H \rightarrow \mu\tau$ has received 66 citations…
● CMS paper on $H \rightarrow \mu \tau$ has received 66 citations…

I think the theorists, like lawyers, are chasing an ambulance
I don’t think there is an ambulance

I think the theorists, like lawyers, are chasing an ambulance

CMS paper on $H \rightarrow \mu \tau$ has received 66 citations…