Searches for the Higgs at the LHC in the ZZ decay channel (non 4l)

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Outline

ATLAS and CMS accumulated ~5fb$^{-1}$ data both at $\sqrt{s} = 7$ TeV in 2011 and at $\sqrt{s} = 8$ TeV in 2012, and searched for the Standard Model Higgs boson in various decay channels. This talk reports the searches for the SM Higgs in ZZ decay channels (non-4l) mainly in the high mass region (>200GeV).

• Introduction
• $H \rightarrow ZZ \rightarrow \ell^+\ell^-\nu\bar{\nu}$ in ATLAS and CMS
• $H \rightarrow ZZ^{(*)} \rightarrow \ell^+\ell^-qq$ in ATLAS and CMS
• $H \rightarrow ZZ \rightarrow \ell^+\ell^-\tau^+\tau^-$ in CMS
• Summary
Introduction
Search Processes for $H \rightarrow ZZ$ (non 4\ell)

- $H \rightarrow ZZ \rightarrow \ell^+ \ell^- \nu \bar{\nu}$
  
  CMS-PAS-HIG-12-023 (7TeV+8TeV)

- $H \rightarrow ZZ \rightarrow \ell^+ \ell^- q \bar{q}$
  
  $H \rightarrow ZZ^{(*)} \rightarrow \ell^+ \ell^- q \bar{q}$

- $H \rightarrow ZZ \rightarrow \ell^+ \ell^- \tau^+ \tau^-$
  
  CMS-PAS-HIG-12-016 (7TeV+8TeV combined with 4l analysis)

- Analyses are based on 2011 data at $\sqrt{s}=7$ TeV and 2012 data at 8 TeV

  ATLAS: 4.7 fb$^{-1}$ (7 TeV)
  CMS: 4.6 fb$^{-1}$ (7 TeV) for $\ell^+ \ell^- q \bar{q}$
  5.0 fb$^{-1}$ (7 TeV) + 5.0 fb$^{-1}$ (8 TeV) for $\ell^+ \ell^- \nu \bar{\nu}$
  5.05 fb$^{-1}$ (7 TeV) + 5.26 fb$^{-1}$ (8 TeV) for $\ell^+ \ell^- \tau^+ \tau^-$
SM Higgs Boson \( \sigma \times BR \)


- Uncertainty of mass line shape:
  \[ \sim (150\%) \times \left( \frac{M_H}{\text{TeV}} \right)^3 \]
  for \( M_H \geq 300 \) GeV

- Main decay modes of the high mass SM Higgs boson are decays to vector boson pairs.
Sensitivity of the Search

- In the high Higgs mass region, $H \rightarrow ZZ \rightarrow \ell^+\ell^-\ell^+\ell^-$ has the largest sensitivity.
Analyses
\[ H \rightarrow ZZ \rightarrow \ell^+\ell^- \nu\bar{\nu} \] (ATLAS)

- High \( p_T \) lepton pair and large \( E_T^{\text{miss}} \) from \( Z \) decays.
- Exactly two oppositely charged leptons \( p_T > 20 \text{ GeV} \ (e^+e^-, \mu^+\mu^-) \) (3rd lepton veto with \( p_T > 10 \text{ GeV} \))
- \(|m_Z - m_{\ell\ell}| < 15 \text{ GeV}\)
- \( m_H \) in \([200, 600]\) \text{ GeV}, 4-sub channels:
  - \((ee, \mu\mu) \otimes \) (high, low) pile-up periods
- \( b \)-jet veto: \( p_T > 20 \text{ GeV}, |\eta| < 2.5 \)
- Optimize selections for two \( m_H \) regions:
  - \( 200 < m_H < 280 \text{ GeV} \)
  - \( 280 \leq m_H < 600 \text{ GeV} \)
  - \( E_T^{\text{miss}} > 66 \text{ GeV} \)
  - \( 1 < \Delta\phi(\ell, \ell) < 2.64 \)
  - \( \Delta\phi(p_T^{\text{miss}}, p_T^{\text{jet}}) > 1.5 \)
  - \( m_T^2 \equiv \left[ \sqrt{m_Z^2 + |p_T^{\ell\ell}|^2} + \sqrt{m_Z^2 + |p_T^{\text{miss}}|^2} \right]^2 - |p_T^{\ell\ell} + p_T^{\text{miss}}|^2 \)

\[ \Delta\phi(p_T^{\text{miss}}, p_T^{\text{jet}}) \text{ [rad]} \]

\[ E_T^{\text{miss}} \text{ [GeV]} \]

\[ \text{Events / 5 GeV} \]

\[ \text{Data / MC} \]

\[ \text{Low pile-up data} \]

\[ \text{Data} \int L \ dt = 2.3 \text{ fb}^{-1} \]

\[ \text{Total Background} \]

\[ \text{Top} \]

\[ \text{ZZ, WZ, WW} \]

\[ \text{Z} \]

\[ \text{Other Backgrounds} \]

\[ \text{Signal (} m_H = 200 \text{ GeV}) \]

\[ \text{Signal (} m_H = 400 \text{ GeV}) \]
Most BG estimated from MC and verified with data.

- WZ: verified with three-lepton events
- Top: verified in two control samples: \((e^\pm \mu^\mp)\), and \(b\)-jet + \(m_\ell\ell\) side-band.
- W + jets: verified with like-sign \((e^\pm e^\pm, \mu^\pm \mu^\pm)\)
- Z + jets: verified with events rejected by \(\Delta \phi(P_{miss}, \vec{P}_{jet})\)

- No indication of excess is seen in \(m_T\) distributions.

\(319 < m_H < 558\) GeV excluded at the 95% CL.
\[ H \rightarrow ZZ \rightarrow \ell^+ \ell^- \nu \bar{\nu} \] (CMS)

- Two sub-categories
  - VBF: two or more jets \(|\Delta \eta_{jj}| > 4\), \(m_{jj} > 500\) GeV
    - leptons are in between jets, no jets in the central
  - Gluon Fusion: all other events (0-, 1- and ≥2 jets)
- \(|m_Z - m_{\ell\ell}| < 30\) GeV, \(p_T^{\ell\ell} > 55\) GeV and
  \(\Delta \phi(E_T^{\text{miss}}, p_T^{\text{jet}}) > 0.5\) with 3rd lepton veto
  \(p_T > 10\) GeV
- Top rejection
  - b-jet veto: \(p_T > 30\) GeV, \(|\eta| < 2.4\)
  - soft \(\mu\) veto: \(p_T > 3\) GeV
- \(m_H\) dependent cuts on \(E_T^{\text{miss}}\) and \(m_T\) for “Gluon Fusion”. Fixed \(E_T^{\text{miss}} > 70\) GeV cut for “VBF”.

Backgrounds:
- ZZ and WZ from MC
- Z + jets modeled with \(\gamma +\) jets events
- Non-resonant backgrounds (no Z included)
  - from \((e^\pm \mu^{\mp})\) control sample with scale factors
    obtained from number of events in \(m_Z\) side-bands
No significant excess of events is observed
The SM Higgs boson is excluded at 95% confidence level:

\[ 278 \text{ GeV} < m_H < 600 \text{ GeV} \]

\[ H \rightarrow ZZ \rightarrow \ell^+ \ell^- \nu \overline{\nu} \] (CMS)
$H \rightarrow ZZ^{(*)} \rightarrow \ell^+ \ell^- q\bar{q}$ (CMS)

- Highest $\sigma \times \text{Br}$ of all $H \rightarrow ZZ$ modes
- $m_H$ regions: [125,170], [183,800] GeV
- lepton:
  - low $m_H$: $p_T^\ell > 20$, 10 GeV, $m_{\ell\ell} < 80$ GeV
  - high $m_H$: $p_T^\ell > 40$, 20 GeV, $70 < m_{\ell\ell} < 110$ GeV
- jet: $p_T^{\text{jet}} > 30$ GeV, $75 < m_{jj} < 105$ GeV
- Events categorized by 0, 1, 2 $b$-jets
- Higgs decay angles: angular likelihood discriminant (LD) based on $(\theta^*, \Phi_1, \theta_1, \theta_2, \Phi)$
- Quark-gluon LD for 0 $b$-jets: no. of charged tracks, no. of photon and neutral hadrons, and $\text{PTD} = \sqrt{\sum p_T^2 / (\sum p_T)^2}$
- Missing $E_T$ discriminant for top: $E_T^{\text{miss}} \sim 0$

Background
- $m_{jj}$ sidebands: $60 < m_{jj} < 75$ GeV and $105 < m_{jj} < 130$ GeV
$H \rightarrow ZZ^{(*)} \rightarrow \ell^+\ell^- q\bar{q}$ (CMS)

- SM Higgs: the upper limit of cross section at the 95% CL for the search regions.
- A Higgs model with four fermion generations: [154,161] GeV and [200, 470] GeV are excluded at 95% CL.
\[ H \rightarrow ZZ \rightarrow \ell^+\ell^- q\bar{q} \] (ATLAS)

- High \( p_T \) lepton pair and jet pair from \( Z \) decays. Small \( E_T^{\text{miss}} \)
- \( m_H \) region: 200-600 GeV
- \( e, \mu : p_T^\ell > 20 \text{ GeV}, 83 < m_{\ell\ell} < 99 \text{ GeV} \)
  jet : \( p_T^{\text{jet}} > 20 \text{ GeV}, 70 < m_{jj} < 105 \text{ GeV} \)
  \( \Delta R_{jj} > 0.7 \)
- \( E_T^{\text{miss}} < 50 \text{ GeV} \)
- Two sub-channels: untagged (\(< 2 b \) jets) & tagged (\(= 2 b \) jets)
- For high \( m_H (> 300 \text{ GeV}) \)
  \( p_T^{\text{jet}} > 45 \text{ GeV}, \Delta \phi_{\ell\ell} < \frac{\pi}{2}, \Delta \phi_{jj} < \frac{\pi}{2} \)

Backgrounds
- \( Z + \text{jets} \): \( m_{jj} \) sidebands: [40,70], [105,150] GeV
- Top: \( m_{\ell\ell} \) sidebands: [60,76], [106,150] GeV and \( E_T^{\text{miss}} \) selection reversed.
- Di-boson: from MC simulation
- Multi-jet: events with loose electron-ID
\[ H \rightarrow ZZ \rightarrow \ell^+ \ell^- q\bar{q} \quad (\text{ATLAS}) \]

- \(m_{lljj}\) distributions: no significant excess of events is seen.

- \(300 \leq m_H \leq 322\) GeV and \(353 \leq m_H \leq 410\) GeV excluded at the 95\% CL.
\[ H \rightarrow ZZ \rightarrow \ell^+\ell^- \tau^+\tau^- \quad \text{(CMS)} \]

- This analysis becomes a part of \( ZZ \rightarrow 4\ell \) analysis for 7+8 TeV data.

- One \( Z \): \( Z \rightarrow \ell^+\ell^- (\ell = e, \mu) \)
  \[ 60 < m_{\ell\ell} < 120 \text{ GeV} \quad (p_T^\ell > 20 \text{ GeV} \text{ and } 10 \text{ GeV}) \]

- The other: \( Z \rightarrow \tau^+\tau^- \)
  \( \tau_h\tau_h, \tau_e\tau_h, \tau_\mu\tau_h \text{ and } \tau_e\tau_\mu \) are considered.
  Visible mass: \( m_{\tau\tau} < 90 \text{ GeV} \)
  \[ (p_T^\ell > 10 \text{ GeV} \text{ and } p_T^{\tau_h} > 20 \text{ GeV}) \]

- Results combined with 4l-channel:
  The SM Higgs boson excluded to 525 GeV
  95% CL. (tau-channel contribution is small)
  (Corresponding number from ZZ->4l by ATLAS: 460 GeV)
Summary and Outlook

- SM Higgs boson searches in the high mass region have been performed by ATLAS and CMS, using the H to ZZ decay channel. In combination with other channels a SM Higgs boson is excluded up to 600 GeV.

- As the next step:
  - to probe higher mass region, and
  - to search for non-SM signals.
Backups
SM Higgs Boson Decays

![Graph showing SM Higgs Boson Decays](image)

**Higgs BR + Total Uncert**

- $b\bar{b}$
- $WW$
- $ZZ$
- $\tau\tau$
- $gg$
- $c\bar{c}$
- $\gamma\gamma$
- $Z\gamma$

**$M_H$ [GeV]**

- $100$
- $200$
- $300$
- $400$
- $500$
- $1000$

**LHC HIGGS XS WG 2011**
SM Higgs Boson Production

\[ \sigma(pp \rightarrow H+X) \text{ [pb]} \]

- \( pp \rightarrow H (\text{NNLO+NNLL QCD + NLO EW}) \)
- \( pp \rightarrow qqH (\text{NNLO QCD + NLO EW}) \)
- \( pp \rightarrow WH (\text{NNLO QCD + NLO EW}) \)
- \( pp \rightarrow ZH (\text{NNLO QCD + NLO EW}) \)
- \( pp \rightarrow t\bar{t}H (\text{NLO QCD}) \)

\[ \sqrt{s} = 7 \text{ TeV} \]

\[ M_H [\text{GeV}] \]

100 - 1000

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\[ H \rightarrow ZZ \rightarrow \ell^+\ell^- \nu\bar{\nu} \] (ATLAS)

- High pile-up plots

### High pile-up plots

**ATLAS 2011 \( \sqrt{s} = 7 \) TeV**

- Data \( \int L dt = 2.4 \) fb\(^{-1}\)
- Total Background
- Top
- ZZ, WZ, WW
- Z
- Other Backgrounds
- Signal \((m_H = 200 \) GeV\)
- Signal \((m_H = 400 \) GeV\)

#### 1. \( E_T^{\text{miss}} \) vs. \( E_T^{\text{miss}} \) [GeV]

#### 2. \( \Delta\phi(\vec{p}_T^{\text{miss}}, \vec{p}_T^{\text{jet}}) \) [rad]
\[ H \rightarrow ZZ \rightarrow \ell^+\ell^- \nu\bar{\nu} \] (ATLAS)

• High pile-up plots
$H \rightarrow ZZ \rightarrow \ell^+ \ell^- \nu \bar{\nu}$ (CMS)

- 7TeV Plots
$$H \rightarrow ZZ^{(*)} \rightarrow \ell^+ \ell^- q\bar{q}$$  (CMS)
$H \rightarrow ZZ^{(*)} \rightarrow \ell^+\ell^- q\bar{q}$ (CMS)

CMS, $L = 4.6$ fb$^{-1}$ at $\sqrt{s} = 7$ TeV

- Data
  - $Z + \text{jets}$
  - $ZZ/WZ/WW$
  - $t\bar{t}/tW$

$H(400 \text{ GeV}) \times 100$
$H \rightarrow ZZ^{(*)} \rightarrow \ell^+\ell^- q\bar{q}$  (CMS)

- 0 b-tag Category
$H \rightarrow ZZ^{(*)} \rightarrow \ell^+\ell^- q\bar{q}$ (CMS)

- 1 b-tag Category

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**1 b-tag Category**

**Data**

- Expected background
- $H(150 \text{ GeV}) \times 5$
- $Z$ + jets
- $ZZ/WZ/WW$
- $t\bar{t}/tW$

**Expected background**

- $H(400 \text{ GeV}) \times 2$
- $Z$ + jets
- $ZZ/WZ/WW$
- $t\bar{t}/tW$

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CMS, $L = 4.6 \text{ fb}^{-1}$ at $\sqrt{s} = 7 \text{ TeV}$
\[ H \rightarrow ZZ \rightarrow \ell^+ \ell^- q\bar{q} \] (ATLAS)

- Tagged control plots
$H \rightarrow ZZ \rightarrow \ell^+ \ell^- q\bar{q}$ (ATLAS)

- $m_H = 200$ GeV