Extended Scalar Searches at ATLAS & CMS

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Rencontres de Moriond EW 2016
Beyond the Standard Model

The observed Higgs boson at 125 GeV could be only the beginning.

A few examples out of many...

Higgs Triplet:
An additional scalar triplet results in charged, doubly-charged, and neutral bosons.

Two-Higgs Double Models (2HDM):
Additional Higgs Doublet gives rise to 5 Higgs bosons (H,h,A,H±)

2HDM+S:
Two Higgs Doublets and an additional complex singlet (e.g. NMSSM)

Electroweak Singlet (EWS):
Additional singlet, resulting in 2 CP-even bosons.

Minimal Supersymmetric Standard Model:
Higgs Sector is Type-II 2HDM. Current common benchmark is hMSSM.

BSM physics was not observed in run-1, but there are still many possible models to be investigated in run-2.
Run-1 Results/Run-2 Prospects

• Many searches were performed in run-1, with 7 and 8 TeV centre-of-mass energy at the LHC, but physics beyond the Standard Model has not yet been observed.

• An example of where we stand and hopes for the future of the LHC can be seen in the hMSSM overlay and prospect plots.
  – Much parameter space is excluded, but there is still room for high mass Higgs to be found!

In 2015, ATLAS collected 3.2 fb⁻¹ and CMS collected 2.8 fb⁻¹ of data at 13 TeV!

This is already enough in many cases to exceed run-1 sensitivity!
Beyond the Standard Model Searches in this Presentation

Many searches for run-2, as well as a few final searches for run-1, from ATLAS, CMS, and both.

**Charged Higgs**
- $H^\pm \rightarrow \tau \nu$ (13 TeV)
- $H^\pm \rightarrow tb$ (8 TeV)
- $\phi^{\pm\phi^{\pm}} \rightarrow lll\nu/4l$ (8 TeV)

**Neutral Higgs**
- $H \rightarrow \tau\tau$ (13 TeV)

**Higgs-to-Higgs**
- $H \rightarrow 2a$ (8 TeV)
- $H \rightarrow ZA$ (13 TeV)
- $A \rightarrow Zh(125)$ (13 TeV)

**Di-Higgs**
- $H \rightarrow hh \rightarrow bb\gamma\gamma$ (13 TeV)
- $H \rightarrow hh \rightarrow bb\tau\tau$ (8/13 TeV)

**Dibosons**
- $H \rightarrow ZZ \rightarrow 4l$ (13 TeV)
- $H \rightarrow ZZ \rightarrow ll\nu\nu$ (13 TeV)
- Boosted Resonances (13 TeV)
  - $H \rightarrow ZZ \rightarrow llqq$ (13 TeV)
  - $ZH, H \rightarrow inv$ (13 TeV)
  - $X \rightarrow Z\gamma$ (13 TeV)
Recent vs = 8 TeV Results
In a 2HDM+S model, there are 2 singlet states:
- CP-odd scalar $a$
- CP-even $s$

BR($h \rightarrow$ BSM) < 0.34, so the decay to 2a can be sizeable.

Recent results from CMS for $h \rightarrow 2a \rightarrow 2b2\mu$ and $h \rightarrow 2a \rightarrow 2\mu2\tau$!

Current channels include:
- $h \rightarrow 2a \rightarrow 2b2\mu$ (CMS-PAS-HIG-14-041)
- $h \rightarrow 2a \rightarrow 4\mu$ (CMS: Phys. Lett. B 752 (2016) 221)
- $h \rightarrow 2a \rightarrow 4\tau$ (CMS-PAS-HIG-14-022, CMS: JHEP 01 (2016) 079)
- $h \rightarrow 2a \rightarrow 4\gamma$ (ATLAS: CERN-PH-EP-2015-187)
2HDM+S: Search for $h(125) \rightarrow 2a$

$h \rightarrow 2a \rightarrow 2b2\mu$: 
2 b-jets, 2 $\mu$, $E_T^{\text{miss}}$ significance < 6
$\left| M_{bb\mu\mu} - 125 \right| < 25$ GeV

**Signal Modeling:** Weighted sum of Voigt profile and Crystal ball.

**Background Modeling:** Polynomial functions, fit to $m_{\mu\mu}$ in data.

$h \rightarrow 2a \rightarrow 2\mu2\tau$
5 final states: $\mu\mu\tau_e\tau_e$, $\mu\mu\tau_\mu\tau_\mu$, $\mu\mu\tau_{\text{had}}\tau_e$, $\mu\mu\tau_{\text{had}}\tau_\mu$, $\mu\mu\tau_{\text{had}}\tau_{\text{had}}$

$\left| M_{\tau\tau\mu\mu} - 125 \right| < 25$ GeV
$(M_{\mu\mu} - M_{\tau\tau})/M_{\mu\mu} < 0.8$
$\left| M_{\text{vis}_{ee\mu\mu}} - 125 \right| > 15$ GeV

Irreducible backgrounds from MC, reducible from data-driven methods.
Predicted in models with extended Higgs Sector (e.g. 2HDM):

- H± dominantly produced in association with a top quark.
- H± → tb is a dominant decay mode for heavy H±.

Search in lepton+jets final state. Fit is performed on 5 regions:
- $H_T^{\text{had}}$ in 4 Control Regions: [4j(2b), 5j(2b), ≥6j(2b), 4j(≥3b)]
- BDT in 1 Signal Region: [≥5j(≥3b)]

BDT includes $H_t^{\text{had}}$, lead jet $p_T$, $m_{bb}$ of 2 b-jets closest in ΔR, second Fox-Wolfram moment, and average ΔR between all b-jet pairs.
Higgs Triplets: Search for $H^{\pm\pm}$

- $H^{\pm\pm}$ is predicted by models with a Higgs triplet.

- This search is for associated production or pair-produced left-handed $H^{\pm\pm}$ into 3 or 4 leptons, respectively.
Scalar Resonance: $H \rightarrow hh \rightarrow bb\tau_{had}\tau_{had}$

2 hadronic $\tau_{had}$ and 2 jets
$80 < m_{\tau\tau} < 140$ GeV and $80 < m_{jj} < 170$ GeV
$m_{HH}$ calculated using a kinematic fit

**Backgrounds**
Multi-jet: Data-driven methods
$Z/\gamma^* \rightarrow \tau_{had}\tau_{had}$: Embedding of $\mu\mu$ data events
Others: Simulation

Fit to three regions with 0, 1, or 2 b-tagged jets.

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**CMS Preliminary** 18.3 fb$^{-1}$ (8 TeV)

**2jet0tag**
- Resonant
- $X \rightarrow HH \rightarrow bb\tau\tau$
- Observed
- $Z \rightarrow \tau\tau$
- $t\bar{t}$
- Electroweak
- Multijets
- SM Higgs
- Uncertainty

**2jet1tag**
- Resonant
- $X \rightarrow HH \rightarrow bb\tau\tau$
- Observed
- $Z \rightarrow \tau\tau$
- $t\bar{t}$
- Electroweak
- Multijets
- SM Higgs
- Uncertainty

**2jet2tag**
- Resonant
- $X \rightarrow HH \rightarrow bb\tau\tau$
- Observed
- $Z \rightarrow \tau\tau$
- $t\bar{t}$
- Electroweak
- Multijets
- SM Higgs
- Uncertainty

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See Seth Zenz’s talk for non-resonant analysis.
$\sqrt{s} = 13$ TeV Searches: 
Fermionic Decays
Search for $H^\pm \rightarrow \tau \nu$

$H^\pm$ predicted in 2HDM/MSSM:

✓ $H^\pm$ dominantly produced in association with a top quark.

✓ $H^\pm \rightarrow \tau \nu$ decay channel represents a clean signature and substantial BR ($\sim 10\%$) in several MSSM benchmarks.

Search is for the decays:

$$
\begin{align*}
g\bar{b} & \rightarrow [\bar{t}] [H^+] \rightarrow [q\bar{q}b] [\tau^+_{\text{had-vis}} + \nu_\tau] \\
gg & \rightarrow [\bar{t}b] [H^+] \rightarrow [(q\bar{q}b)b] [\tau^+_{\text{had-vis}} + \nu_\tau]
\end{align*}
$$

with the final discriminating variable:

$$m_T = \sqrt{2p_T^\tau E_{\text{miss}}^\tau (1 - \cos \Delta \phi_{\text{had-vis,miss}})}$$
Search for $H^\pm \rightarrow \tau \nu$

Backgrounds:
- **Jet → τ fakes** (multi-jet: data-driven)
- **Events with true τ** (tt, W+jets: from MC, validated in CR)
- **Events with lepton → τ fakes** (top, V+jets, diboson: Shape from MC, norm. from data. ~5% of background.)

Event Selection
- $E_T^{\text{miss}}$ trigger
- ≥3 jets including ≥1 b-tagged jet
- 1 τ and no e or μ
- $E_T^{\text{miss}} > 150$ GeV
- $m_T > 50$ GeV

**ATLAS Preliminary**
$\sqrt{s} = 13$ TeV, 3.2 fb$^{-1}$
$H^+ \rightarrow \tau \nu$; hMSSM scenario
- Observed exclusion
- Expected exclusion
- ± 1σ
- ± 2σ

Observed exclusion
Expected exclusion
± 1σ
± 2σ
H$^+$ hMSSM tanβ=60

Run 1 result
- Observed
- Expected

Observed (CLs)
Expected (CLs)

CERN-PH-EP-2016-056
Search for $H/A \rightarrow \tau\tau$

$H\rightarrow\tau\tau$ provides sensitivity in MSSM at high $\tan\beta$, and in 2HDM at the alignment limit.

Analysis targets two channels with different $\tau$ decay modes.

**\(\tau_{\text{lep}}\tau_{\text{had}}\) Event Selection**

- Single lepton triggers
- 1 $\tau$ and 1 OS e/\mu and $\Delta\phi(\tau, e/\mu) > 2.4$
- $M_T(e/\mu, \text{MET}) < 40 \text{ GeV}$ or $> 150 \text{ GeV}$
- In e-channel: $m_{\text{vis}} < 80$ and $> 110 \text{ GeV}$

**\(\tau_{\text{had}}\tau_{\text{had}}\) Event Selection**

- Single $\tau_{\text{had}}$ trigger
- 2 $\tau_{\text{had}}$ with OS charge
- $\Delta\phi(\tau_{\text{had},1}, \tau_{\text{had},2}) > 2.7$

Final discriminant in both channels

\[
m_T^{\text{total}} = \sqrt{m_T^2(\tau_1, \tau_2) + m_T^2(\tau_1, E_T^{\text{miss}}) + m_T^2(\tau_2, E_T^{\text{miss}})}
\]
Search for H/A → ττ

Backgrounds

✓ **True τ backgrounds** (e.g. Z → ττ, tt) are taken from simulation.

✓ **Jet → τ backgrounds** (e.g. W+jets, multi-jets) are estimated using data-driven methods.

No evidence for BSM Higgs, but sensitivity already exceeds run-1.
$\sqrt{s} = 13$ TeV Searches: Di-Higgs
Search for $H \rightarrow hh \rightarrow bb\gamma\gamma$

hh production can be resonantly enhanced by many BSM models (Singlet, MSSM, etc.).

- $bb\gamma\gamma$ chosen due to high BR($h \rightarrow bb$) and clean $\gamma\gamma$ signature.
- ATLAS has also searched for $hh \rightarrow 4b$, covered in Max Bellomo’s talk tomorrow.

**Event Selection**

- $2\gamma$ within $105 < m_{\gamma\gamma} < 160$ GeV
- 2 central jets within $95 < m_{jj} < 135$ GeV
- 2 (0) b-tag as SR (CR) at 85% efficiency
- $bb$ 4-momenta scaled by $m_h/m_{bb}$

\[ |m_{\gamma\gamma} - m_h| < 2\sigma(m_{\gamma\gamma}) \]

$M_{bb\gamma\gamma}$ within window of 95% signal efficiency

See Seth Zenz’s talk for non-resonant analysis.
Search for \( H \rightarrow hh \rightarrow bb\tau\tau \)

Search for three channels:
\[ \tau_{\text{had}}\tau_\mu, \tau_{\text{had}}\tau_e \] and \( \tau_{\text{had}}\tau_{\text{had}} \)

Exactly two OS objects, as above
2 b-tagged jets

Final mass variable \( m_H \) constructed using a kinematic fit.

**Backgrounds**

- **Multi-jet**: estimated using data-driven methods

- **Z+jets**: MC corrected using data control regions.

- **tt**: MC, shape corrected by top pT reweighting.

- **Others** (W+jets, single top, diboson) from MC.
Search for H→hh→bbττ

Search for three channels: τ_hadτ_μ, τ_hadτ_e and τ_hadτ_had

Exactly two OS objects, as above

2 b-tagged jets

Final mass variable m_H constructed using a kinematic fit.

**Backgrounds**

- **Multi-jet**: estimated using data-driven methods

- **Z+jets**: MC corrected using data control regions.

- **tt**: MC, shape corrected by top pT reweighting.

- **Others** (W+jets, single top, diboson) from MC.

See Seth Zenz’s talk for non-resonant analysis.
Vs = 13 TeV Searches: Higgs to Bosons
Search for $H \rightarrow ZZ \rightarrow 4l$

The 4l final state gives a clean signature with low background, predicted in EWS and 2HDM. The search is for a resonance of $m_H = 140 (200)-1000$ GeV for CMS (ATLAS).

Search is based on selection from $h(125) \rightarrow ZZ \rightarrow 4l$ analysis.
Search for $H \rightarrow ZZ \rightarrow 4l$

The results have also been interpreted in Type-I and Type-II 2HDM.

Search is based on selection from $h(125) \rightarrow ZZ \rightarrow 4l$ analysis.
Search for $H \rightarrow ZZ \rightarrow ll\nu\nu$

Searching for an additional scalar boson, as predicted in EWS/2HDM. The search is for a narrow resonance of $m_H = 300$-1000 GeV (ATLAS) or 200-1500 GeV (CMS).

In both cases, search is for 2 leptons (e or $\mu$) and high $E_T^{\text{miss}}$.

**Backgrounds**

- **ZZ/WZ**: From simulation, WZ scaled using data-driven methods (ATLAS)
- **Others**: Predicted using data-driven methods.

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**CMS: Data-driven Z+jets prediction**

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**ATLAS: WZ Control Region**
**Event Selection**

- 2 same flavor, opposite sign charge leptons
- $76 < m_{ll} < 106$ GeV and $E_T^{\text{miss}} > 120$ GeV
- $\Delta R_{ll} < 1.8$ and $\Delta \phi(Z, E_T^{\text{miss}}) > 2.7$
- Fractional $p_T$ difference $< 0.2$
- $\Delta \phi(\text{jet (pT > 100 GeV)}, E_T^{\text{miss}}) > 0.4$
- $Z_{pT}/M_{T} < 0.7$ and no b-jet

**Final Discriminant:**

$$m_Z^2 = (\sqrt{m_Z^2 + |p_T^1|^2} + \sqrt{m_Z^2 + |E_{T}^{\text{miss}}|^2})^2 - |p_T^1 + E_{T}^{\text{miss}}|^2$$

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**Graph:**

**ATLAS Preliminary**

13 TeV, 3.2 fb$^{-1}$

- **H → ZZ → llvv**

**95% Limit on $\sigma_{ggF} * \text{BR}(H → ZZ) [fb]$**

- **Expected Median**
- **Expected ±1σ**
- **Expected ±2σ**
- **Observed**

**Data/SM Pred.**

**ATLAS Preliminary**

- ggF H (300 GeV)
- ggF H (600 GeV)
- ggF H (1000 GeV)
- W→ZZ
- Zgg
- Z(μν/μν)+jets
- WW/Z(ττ)+jets/WW
- 3W/2ZZ jets
- Triboson
- Fake Lepton

**Stat. ± Syst. Unc.**
**Event Selection**

2 same flavor, opposite sign charge leptons

$E_T^{\text{miss}} > 125 \text{ GeV}$ and $\Delta\phi(\text{nearest jet, } E_T^{\text{miss}}) > 0.5$

No b-tagged jets

**3 Signal Region Categories:**

- **VBF:** $\geq 2$ forward jets with $|\Delta\eta| > 4$ and $m > 500$ GeV.
- $\geq 1 \text{ jets}:$ at least 1 jet, fails VBF
- $= 0 \text{ jets}:$ No jets.

**Final Discriminant:**

$$M_T^2 = \left( \sqrt{p_T(\ell\ell)^2 + M(\ell\ell)^2 + E_T^{\text{miss}}^2 + M_T^2} - (p_T(\ell\ell) + E_T^{\text{miss}}) \right)^2$$

EWS, VBF production
Several diboson resonance searches in ATLAS have also been interpreted in terms of a heavy Higgs-like boson.
  – For details of the analyses, see Max Bellomo’s talk Thursday.

Limits are set up to 3 TeV:
  • For $H \rightarrow WW \rightarrow l\nu qq$, $H \rightarrow ZZ \rightarrow llqq$ and $H \rightarrow ZZ \rightarrow \nu\nu qq$
  • In the narrow width approximation, as well as for widths ranging from 5-15%.
  • No evidence for boosted scalar resonances has been found in any channel.
Search for $H \rightarrow ZZ \rightarrow llqq$

**Merged Analysis**

2 same flavor leptons and 1 large-R jet ($p_T > 200$ GeV) consistent with $Z$ decay

$$P_T(ll) > 0.3m_{ll}$$

**Resolved Analysis**

2 same flavor leptons and 2 small-R jets consistent with $Z$ decay

$$\sqrt{P_T^2(\ell\ell) + P_T^2(jj)} / m_{\ell\ell jj} > 0.5$$

Two categories: 2 and <2 b-tagged jets
Motivated by supersymmetry, search is for a scalar boson, \( H \), with \( m = 110-600 \) GeV, decaying to invisible particles.

**Analysis Selection**

2 same flavor OS e or \( \mu \)

\[ |m_{ll} - m_Z| < 15 \text{ GeV and } p_T^{ll} > 60 \text{ GeV} \]

\( \leq 1 \) jet, no b-jets or soft muons

\( E_T^{\text{miss}} > 100 \) GeV, \( \Delta \phi(\text{ll}, E_T^{\text{miss}}) > 2.8 \) and

\[ |E_T^{\text{miss}} - p_T^{ll}| / p_T^{ll} < 0.4 \]

Final discriminating variable is:

\[ m_T = \sqrt{2 p_T^{ll} E_T^{\text{miss}} (1 - \cos \Delta \phi(\text{ll}, E_T^{\text{miss}}))} \]

which must be > 200 GeV.
Search for A→Zh(125), h→bb

Searching for an additional pseudoscalar boson, as predicted in 2HDM. The search is for a narrow resonance of \( m_H = 200-2000 \) GeV.

### Analysis Strategy

- Targeting A→Zh→ννbb/llbb
- Makes use of categories:
  1. 0/2-leptons
  2. \( p_T^Z < \) or \( > 500 \) GeV (defining the resolved/boosted transition)
  3. 1/2 b-tagged jets
- Final discriminant is invariant \( m_{llbb} \) for 2-lepton and for 0-lepton:

\[
    m_{T,Zh} = \sqrt{(E_T^h + E_{T,miss}^m)^2 - (p_T^Z + E_{T,miss}^m)^2}
\]

See talk in YSF4 by Carlo Pandini for more details.

Dominant backgrounds of Z+jets and ttbar are validated and constrained in control regions.
Search for $A \rightarrow Zh(125)$, $h \rightarrow bb$

Limits on ggF and b-associated production from simultaneous binned-likelihood fit for signal and control regions.
Motivated by 2HDM with twisted custodial symmetry, which gives a heavier scalar $H$ and a lighter pseudoscalar $A$ boson.

**Analysis Strategy**

A signal region (S) is defined for each $m_A-m_H$ hypothesis in the plane of $m_{bb}-m_{llbb}$

tt and Drell-Yan processes are corrected through a fit to data of the $m_{ll}$ distribution for events not in $S$.

The final limit is calculated from the single bin of $S$. 
Limits are set on cross section times branching ratio for three $m_H$ hypotheses, as a function of $m_A$. 

$\sigma \times \text{BR} = 300\text{ GeV}$

$\sigma \times \text{BR} = 500\text{ GeV}$

$\sigma \times \text{BR} = 800\text{ GeV}$
Search for an additional neutral boson (X), with a narrow width.

**Analysis Strategy**

- **Z→ll (250-1500 GeV):**
  - 2 same flavor, **opposite sign leptons** consistent with Z.

- **Z→qq (720-2750 GeV):**
  - Jets reconstructed as a **single large-radius jet** with pT > 200 GeV.

- Both channels use Zγ invariant mass as a final discriminant.
Search for $X \rightarrow Z\gamma$

**Background Modeling**

- Dominant background is continuum production of $Z+\gamma$ (leptonic) and $\gamma + \text{jets}$ events (hadronic).

- In both, background is smoothly falling spectrum as a function of $m_{\text{inv}}$, parameterized as:

$$f_{\text{bkg}}(m_{\text{inv}}) = N (1 - x^k)^{p_1 + \xi p_2} x^{p_2}$$

Largest deviation from background is $2\sigma$ at 350 GeV.

Observed limits range between 295 fb at $m_X = 340$ GeV to 8.2 fb at $m_X = 2.15$ TeV.
In Summary

• There have already been a variety of searches for extended scalars at 13 TeV, but this is just the beginning!

• Searches investigate a variety of models (2HDM, 2HDM+S, MSSM, etc.) and many final states.

• 2016 should be an interesting year for Beyond-Standard-Model searches in high energy physics!

Public documents for analyses covered in this talk are either available now, or will become available in the following days.
Backup
Search for $H^\pm \rightarrow \tau \nu$

- The Background contributions are split up by the origin of the $\tau$ in the event:
  - Jet $\rightarrow \tau$ fakes (data-driven)
  - Events with true $\tau$ (from MC, validated in CR)
  - Events with lepton $\rightarrow \tau$ fakes (Shape from MC, norm. from data)

Event Selection

- $E_\text{T}^{\text{miss}}$ trigger
- $\geq 3$ jets including $\geq 1$ b-tagged jet
- 1 $\tau$ and no e or $\mu$
- $E_\text{T}^{\text{miss}} > 150$ GeV
- $m_\tau > 50$ GeV

ATLAS Preliminary

$\sqrt{s} = 13$ TeV, 3.2 fb$^{-1}$

W $\rightarrow \tau \nu$ control region

Events / 5 GeV

Data / SM

$m_\tau$ [GeV]

ATLAS Preliminary

$\sqrt{s} = 13$ TeV, 3.2 fb$^{-1}$

$t\bar{t}$ control region

Events / 5 GeV

Data / SM

$m_\tau$ [GeV]
A fake factor (FF) is measured in a multi-jet control region, defined as:

$$FF = \frac{N_{\text{fail}}}{N_{\text{pass}}}$$

where $N_{\text{fail}}$ event $\tau$ candidates fail the full $\tau$ selection, and $N_{\text{pass}}$ pass.

**FF parameterized in:**
- $\tau$ $p_T$
- $\tau$ decay mode,
- Light/heavy flavor bins based on b-tagging algorithm.

**Final Contribution Defined by:**

$$N_{\tau_{\text{had-vis}}}^{\text{fakes}} = \sum_i N_{\text{anti-}\tau_{\text{had-vis}}(i)} \times FF(i),$$
Final discriminant in both channels

\[
m_T^{\text{total}} = \sqrt{m_T^2(\tau_1, \tau_2) + m_T^2(\tau_1, E_T^{\text{miss}}) + m_T^2(\tau_2, E_T^{\text{miss}})}
\]

H → ττ provides sensitivity in MSSM at high tan β, and in 2HDM at the alignment limit. Analysis targets two channels with different τ decay modes.

**τ_{lep} τ_{had} Event Selection**

- Single lepton triggers
  - 1 medium τ, \( p_T > 20 \text{ GeV} \)
  - 1 medium, isolated e/μ, \( p_T > 30 \text{ GeV} \)
  - τ and e/μ of opposite sign charge
  - \( \Delta \phi(\tau, e/\mu) > 2.4 \)
  - \( M_{T}(e/\mu, \text{MET}) < 40 \text{ GeV or } > 150 \text{ GeV} \)

- In e-channel: \( m_{\text{vis}} < 80 \) and \( > 110 \text{ GeV} \)

**τ_{had} τ_{had} Event Selection**

- Single τ_{had} trigger
  - 2 τ_{had} with OS charge
  - No loose e/μ
  - \( \Delta \phi(\tau_{\text{had},1}, \tau_{\text{had},2}) > 2.7 \)

- Leading τ_{had} is medium, trigger-matched, \( p_T > 135 \text{ GeV} \)

- Subleading τ_{had} is loose, \( p_T > 55 \text{ GeV} \)
Search for H/A $\rightarrow \tau\tau$: $\tau_{lep}$ $\tau_{had}$ Backgrounds

True $\tau$ backgrounds ($Z\rightarrow\tau\tau$, $tt$) are taken from simulation. Jet$\rightarrow$\tau backgrounds are estimated using “Combined Fake Factor” Method

\[
\text{Combined FF} = \text{FF}_{W+jets} r_{W+jets} + \text{FF}_{QCD} r_{QCD}
\]

The Combined FF is applied to events where $\tau$ fails ID requirement.
Search for H/A $\rightarrow \tau\tau$: $\tau_{\text{had}}\tau_{\text{had}}$ Backgrounds

- True $\tau$ backgrounds ($Z\rightarrow\tau\tau$, $tt$) are taken from simulation.
- Jet$\rightarrow\tau$ backgrounds are estimated by applying fake rate from data in place of simulated $\tau$ ID response.
- Multi-jet backgrounds are estimated using a fake factor measured in a dijet CR.

Background estimation is validated in same-sign control region.
Expected and Observed events for the ATLAS high mass H→ZZ→4l analysis.
Search for $H \rightarrow hh \rightarrow bb\gamma\gamma$

- **Background:**
  - Continuum from data
  - SM $h$ & $hh$ from MC
  - Cut-and-count in 95% $m_{bb\gamma\gamma}$ window with data-driven continuum background:

$$N_{SR}^B = N_{SB} \frac{\epsilon_{m_{\gamma\gamma}}}{1 - \epsilon_{m_{\gamma\gamma}}} \epsilon_{m_{bb\gamma\gamma}}$$

0 events in mass window
Mass constraint does not dramatically change the background shape.

Limit in terms of # of events.
Search for $X \rightarrow Z\gamma$

Limits split into leptonic and hadronic.
Search for $X \rightarrow Z\gamma$

Comparison of ee and mumu signal resolution

ATLAS Simulation Preliminary

gg$\rightarrow X \rightarrow Z\gamma$, $Z \rightarrow \mu\mu$

$m_X=800$ GeV

$\sqrt{s}=13$ TeV

ATLAS Simulation Preliminary

gg$\rightarrow X \rightarrow Z\gamma$, $Z \rightarrow ee$

$m_X=800$ GeV

$\sqrt{s}=13$ TeV
Search for $H \rightarrow llv\nu$
Boosted Diboson Resonances

• Several diboson resonance searches in ATLAS have also been interpreted in terms of a heavy Higgs-like boson.
  – For details of the analyses, see Max Bellomo’s talk Thursday.

• Limits are set in the narrow width approximation, as well as for widths ranging from 5-15%.
Several diboson resonance searches in ATLAS have also been interpreted in terms of a heavy Higgs-like boson.

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Limits are set in the narrow width approximation, as well as for widths ranging from 5-15%.

Boosted Diboson Resonances

\[ H \rightarrow ZZ \rightarrow \ell\ell q\bar{q} \]

\[ H \rightarrow WW \rightarrow l\nu q\bar{q} \]