Searches for Pseudoscalar Higgs Bosons using the ATLAS Detector

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on behalf of the ATLAS Collaboration

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• Discovery and measurements of a SM-like Higgs boson have “completed” the Standard Model, but still insufficient to fully describe nature
• Supersymmetry provides a possible solution to hierarchy problem and dark matter
  • *Pseudoscalar Higgs bosons appear in variants of SUSY*
• Direct searches for pseudoscalar Higgs bosons
  • MSSM: Searches for A→ττ, μμ (heavy A)
  • NMSSM: Searches for a→μμ; h→aa→4γ (light a)
• Constraints from measurements of observed Higgs boson
  • Probe of Higgs CP in h→ZZ→4l
  • Coupling measurements with all channels → MSSM, 2HDM
• **Searches for pseudoscalar Higgs bosons are important probe of new, fundamental physics at the TeV scale!**
### Pseudoscalars in extended Higgs sectors

<table>
<thead>
<tr>
<th>Model</th>
<th>Higgs sector</th>
<th>CP-odd</th>
<th>SUSY partners</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>2HDM:</strong> Two-Higgs-Doublet-Model</td>
<td>Two doublets $\rightarrow$ 5 Higgs bosons $(h, H, H^+, H^-, A)$</td>
<td>$A$ (heavy)</td>
<td>None</td>
</tr>
<tr>
<td><strong>MSSM:</strong> Minimal Supersymmetric Standard Model</td>
<td>Two doublets $\rightarrow$ 5 Higgs bosons $(h, H, H^+, H^-, A)$</td>
<td>$A$ (heavy)</td>
<td>+ sparticles</td>
</tr>
<tr>
<td><strong>NMSSM:</strong> Next-to-minimal Supersymmetric Standard Model</td>
<td>Two doublets, one singlet $\rightarrow$ 7 Higgs bosons $(h_1, h_2, h_3, H^+, H^-, a_1, a_2)$</td>
<td>$a_1, a_2$ (light)</td>
<td>+ sparticles</td>
</tr>
</tbody>
</table>
Probe of observed Higgs charge-parity

- Observed Higgs boson may have a pseudoscalar component
- BDT trained to use Z masses and lepton angles in $h\rightarrow ZZ\rightarrow 4l$ decays in 7-8 TeV data
- $0^-$ hypothesis excluded at 97.8% CL in favor of $0^+$
  - However CP admixtures still compatible with data
  - At 14 TeV, CP-odd fraction $f_{g4} < 0.18 \ (0.05)$ exp. with 300 \ (3000 fb-1)
    - ATL-PHYS-PUB-2013-013
MSSM: Production modes of $A$

- Simplest low-energy SUSY model with rich & simple Higgs phenomenology
  - $A$ has odd CP, while other Higgs bosons are CP-even
  - Two parameters: $m_A$ and $\tan \beta = \nu_2/\nu_1$
  - Dominant production modes for $A$ are gluon fusion and associated $bbA$
    - $bbA$ can be significantly enhanced at large $\tan \beta \rightarrow$ tag $b$-jets

![Diagram of production modes](image)

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MSSM: Decay modes of A

- Branching ratios for pseudoscalar Higgs
- Dominant decay modes to b-quarks and taus, particularly at large $\tan\beta$
- $\text{BR}(A \rightarrow \tau\tau) \sim 10\%$
  - Better sensitivity at low mass than $A \rightarrow b\bar{b}$ due to large QCD backgrounds
  - Categorized in turn by decay mode of each $\tau$
- $\text{BR}(A \rightarrow \mu\mu) \sim 0.04\%$ but clean signature
Search for A→ττ

- 4.7 fb⁻¹ of 7 TeV data
  - Categorize by final state depending on \( \tau \) decay
  - Triggers:
    - \( \tau_e \tau_\mu (\tau_{lep} \tau_{had}) \): Single or di-lepton (single lepton only)
    - \( \tau_{had} \tau_{had} \): Two hadronic taus
  - Samples split by b-tag or b-veto to distinguish bbA vs. ggF production
  - Discriminating variable, \( m_{\tau\tau} \), estimated via Missing Mass Calculator (MMC)
    - Assume missing \( E_T \) due entirely to neutrinos
    - Scan over angles between neutrinos and tau decay products
    - Pick most likely invariant mass of \( \tau\tau \) pair
  - Dominant irreducible background from Drell Yan: \( Z/\gamma^*\rightarrow\tau\tau \)
    - Embed simulated taus into \( Z/\gamma^*\rightarrow\mu\mu \) data & normalize to simulation
  - Multi-jet background:
    - ABCD method for charge correlation & lepton isolation
  - Systematic uncertainties:
    - Data-driven backgrounds
    - Cross-sections and acceptance for MC samples, including theory
    - Trigger & ID for electrons, muons, and hadronic taus
    - Energy/momentum scale and resolution of objects, particularly calorimeter
**A→τ_eτ_μ**

- **Dilepton**: Exactly one electron and one opposite-charge muon, with \( m_{e\mu} > 30 \text{ GeV} \)
  - Electron (muon) \( p_T > 15 \ (10) \text{ GeV} \) for eμ trigger, or 24 (20) GeV for single lepton trigger
- **Low MET and large \( \Delta\phi(e,\mu) \)** required to reject \( tt\bar{t} \) & diboson backgrounds
- **Low \( H_T \)** required to reduce jet-related backgrounds

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**Data 2011**

- \( m_A = 150 \text{ GeV} \)
- \( \tan \beta = 20 \)

**ATLAS**

- \( \sqrt{s} = 7 \text{ TeV} \)
- \( \int L \ dt = 4.7 \text{ fb}^{-1} \)

**b-tag**

- Events / 30 GeV

**b-veto**

- Events / 10 GeV

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Semi-leptonic channel:
- Single isolated electron (muon) with pT > 25 (20 GeV)
- Hadronic tau required to have opposite charge as lepton
- Demand $m_T(l, \text{MET}) < 30$ GeV to avoid W+jets and ttbar
- Top backgrounds smaller here due to one lepton
**A→τ_{had}τ_{had}**

- **Fully hadronic channel:**
  - Two hadronic taus, one “tight” and one “medium”
  - Opposite charge and p_T>45 & 30 GeV
- Veto on electrons (muons) with p_T > 15 (10) GeV
- MET > 25 GeV for neutrinos and suppress QCD multijets
  - Dominant background coming from multijets, then DY

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**ATLAS**

- √s = 7 TeV, ∫L dt = 4.7 fb⁻¹
- b-tag

**JHEP 02 (2013) 095**

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- Data 2011
- m_χ = 150 GeV, tan β = 20
- Multi-jet
- Z → ττ
- W → τν
- Top
- Bkg. uncertainty

**ATLAS**

- √s = 7 TeV, ∫L dt = 4.7 fb⁻¹
- b-veto

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Search for $A \rightarrow \mu\mu$

- Two isolated muons with $p_T > 20$ & $15$ GeV
- MET < 45 GeV to reduce $tt\bar{t}$ background
- Samples with/without tagged b-jet for $bbA$ vs. $ggF$ and to reject Drell-Yan
- Smooth backgrounds expected to be dominated by $Z \rightarrow \mu\mu$ and $tt\bar{t}$ (left)
- Actual analysis fits smooth background in sidebands above $Z$ pole (right)

\[ m_{\mu\mu} \text{ [GeV]} \]

\[ \int L \, dt = 4.8 \, fb^{-1} \]
\[ \sqrt{s} = 7 \, TeV \]
• No significant excess observed in any \( \tau \tau \) nor \( \mu \mu \) decay mode
  • Upper limits on \( \sigma \times \text{BR} \) at \( \sqrt{s}=7 \text{ TeV} \) for decays into \( \tau \tau \) and \( \mu \mu \) (left)
• Translated into upper limits on \( \tan \beta = \nu_2 / \nu_1 \) as a function of \( m_A \) (right)
  • Dilepton: Sensitive at low mass where hadronic backgrounds are large
  • Semi-leptonic: Sensitive at wide range of masses due to lepton
  • Hadronic: Sensitive at high mass where hadronic backgrounds decrease
• Tightest constraint is \( \tan \beta < 9.3 \) for \( m_A = 130 \text{ GeV} \) @ 95% CL
Search for $Z'\rightarrow\tau\tau$ at high mass

- Search for high-mass $Z'$ decaying via hadronic taus with 20 fb$^{-1}$ of 8 TeV data
  - $\sigma(Z') \cdot BR(Z'\rightarrow\tau\tau) < 0.1$ pb at $m_{Z'} = 500$ GeV
- Search for pseudoscalar Higgs $m_A < 500$ GeV similar, includes single-tau trigger
  - Kinematic acceptance and efficiencies specific for $A$ instead of $Z'$
  - Work on-going to analyze 8 TeV data -- stay tuned for upcoming results!
A→μμ prospects at 14 TeV

- Sensitivity projections at 14 TeV
- Regions with 5σ discovery potential
- Large improvement wrt 7-8 TeV, particularly at large $m_A$
  - $\tan \beta < 37$ (23) for $m_A=500$ GeV at 300 (3000) fb$^{-1}$ with A→μμ alone
- Expected exclusions even larger

![Graph showing $\tan \beta$ vs $m_A$](image1)

![Graph showing $m_A$ vs $\tan \beta$](image2)
Simplified MSSM Constraints from Higgs Couplings

- Measured light Higgs couplings via combination of all channels in 7-8 TeV:
  - vector bosons (W/Z)
  - up-type fermions (top)
  - down-type fermions (b, tau)
- Higgs mass measured as: $m_h \sim 125.5$ GeV
- In MSSM, light Higgs mass $m_h$ is a function of $m_A$ and $\tan \beta$: $m_h^2 = m_Z^2 \cos^2(2\beta) + \delta(m_A, \tan \beta, \ldots)$
- Couplings measurements used to constrain $m_A$ and $\tan \beta$:
  - For $2 < \tan \beta < 10$, $m_A > 400$ GeV
  - Observed limits a bit tighter than expected for SM due to high $h \rightarrow \gamma\gamma$ and $h \rightarrow ZZ$ rates
  - Lower limit on $\tan \beta$ for given $m_A$ is complementary to upper limit from direct searches
2HDM Type II Constraints from Higgs Couplings

7-8 TeV

ATLAS-CONF-2014-010

2HDM Type II

Obs. 95% CL

\( \sqrt{s} = 7 \text{ TeV}: \int L dt = 4.6-4.8 \text{ fb}^{-1} \)

Best fit

\( \sqrt{s} = 8 \text{ TeV}: \int L dt = 20.3 \text{ fb}^{-1} \)

Exp. 95% CL

Combined \( h \rightarrow \gamma\gamma, ZZ^*, WW^* \)

SM

\( h \rightarrow \tau\tau, b\bar{b} \)

- 7-8 TeV measurements of Higgs couplings to vector bosons, up-type & down-type fermions via combination of all channels

- Use to set limits on 2HDM Type II (left)

→ Limits on pseudoscalar couplings (scale as \( \cot \beta \) for top quark, \( \tan \beta \) for b-quark & \( \tau \))

- Doesn’t depend on mixing angle \( \alpha \) between \( h,H \) at tree level

- Higher sensitivity at 14 TeV (right)

14 TeV

ATL-PHYS-PUB-2013-015

- 14 TeV

\( \sqrt{s} = 14 \text{ TeV} \)

Expected 95% CL Limit on 2HDM Type II

\( \int L dt = 300 \text{ fb}^{-1}: \) All unc.

\( \int L dt = 300 \text{ fb}^{-1}: \) No theory unc.

\( \int L dt = 3000 \text{ fb}^{-1}: \) All unc.

\( \int L dt = 3000 \text{ fb}^{-1}: \) No theory unc.

SM
NMSSM: Search for $a \rightarrow \mu \mu$

- NMSSM: Add scalar singlet to MSSM
  - 2 CP-odd Higgs bosons: $a_1$, $a_2$ (typically light)
- Search for inclusive $a \rightarrow \mu \mu$ with 39 pb$^{-1}$ at 7 TeV
  - Active analysis with 8 TeV data
- Require two muons triggered with $p_T > 4$ GeV
- Likelihood ratio using vertex fit and isolation
  - PDFs derived using sidebands
- No significant excess wrt background-only prediction with $\Upsilon$ states
  - Upper limit on rate of 0.1-1.6 fb

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• Search for two collimated (unresolved) pairs of photons using 4.9 fb$^{-1}$ of 7 TeV data
• Two photons with $p_T > 40, 25$ GeV
  • Loosened shower shape requirements sensitive to internal structure of EM shower
• Categories of kinematics not used to be more model-independent
  • Thus $h \rightarrow \gamma \gamma$ contamination is small
• Smooth backgrounds (dominated by QCD diphotons) fitted with sidebands
• No excess observed
  • $\sigma \times \text{BR} < 0.15$ pb for $m_a = 100$ MeV at $\sqrt{s} = 7$ TeV
Conclusions

• Searches performed for pseudoscalar Higgs bosons well-motivated by various scenarios (MSSM, NMSSM, 2HDM)

• No evidence found in direct searches with 7 TeV data
  • Indirect constraints from Higgs CP and coupling measurements (8 TeV data) also consistent with SM

• Although large regions of MSSM parameter space excluded, significant SUSY regions remain compatible with observed Higgs boson!
  • Direct searches on-going with 8 TeV data, which have greater sensitivity
  • Discovery potential will be further enhanced with 14 TeV data

• Stay tuned for further results!
ADDITIONAL INFORMATION
More information (I)


More information (II)

  https://cds.cern.ch/record/1611190

  https://cds.cern.ch/record/1336749

  https://cds.cern.ch/record/1460391
**Tau reconstruction and ID**

**Tau jet reconstruction**

- Tau: \( \tau^+ \)\( \tau^- \)\( \nu_\tau \)
- QCD jet: \( \pi^- \)\( \pi^0 \)\( \pi^+ \)

Seed from aK_{\tau} jets in calorimeter (\( \Delta R = 0 \)).
Associated tracks in \( \Delta R = 0.2 \) of jet axis

**Tau jet identification**

3-prong tau BDT discriminant against jets

**1-prong tau-ID performance against jets**

Inverse Background Efficiency

- 3-prong, \( p_T > 20 \text{ GeV} \)
- 1-prong, \( 40 \text{ GeV} < p_T < 100 \text{ GeV} \)

**Tau jet ID efficiencies**

- ATLAS Preliminary Simulation
- multi-prong, Medium

**Tau jets in DATA**

- ATLAS Preliminary
- \( L_{dd} = 1.55 \text{ fb}^{-1}, \sqrt{s} = 7 \text{ TeV} \)

- Data 2011
- \( \gamma^*Z \rightarrow \tau^+\tau^- \)
- Multijet
- \( W \rightarrow \mu\nu \)
- \( W \rightarrow \tau\nu \)
- \( \gamma^*Z \rightarrow \mu\mu \)
- t\bar{t}
- Diboson

- Events/2.5 GeV

- \( m_{\Delta \nu}(\tau^+\tau^-) \) [GeV]
Di-tau invariant mass reconstruction

Effective (visible or transverse) mass

\[ m_{\tau\tau} = \sqrt{\left( p_{\text{vis1}} + p_{\text{vis2}} + p_{\text{miss}} \right)^2} \]
\[ p_{\text{miss}} = (E^\text{miss}_T, E^\text{miss}_{T_x}, E^\text{miss}_{T_y}, 0) \]

Collinear approximation

\[ m_{\tau\tau} = \frac{m_{\text{vis}}}{(x_1, x_2)^{1/2}} \]
\[ x_1, 2 = \frac{p_{\text{vis1,2}}}{p_{\text{vis1,2}} + p_{\text{miss1,2}}} \]

\[ E^T_x = p_{\text{vis}}, \sin \theta_{\text{vis}}, \cos \phi_{\text{vis}} + p_{\text{miss}} \sin \theta_{\text{miss}}, \cos \phi_{\text{miss}} \]
\[ E^T_y = p_{\text{vis}}, \sin \theta_{\text{vis}}, \sin \phi_{\text{vis}} + p_{\text{miss}} \sin \theta_{\text{miss}}, \sin \phi_{\text{miss}} \]

MMC

(Missing Mass Calculator)

Event by event \( M_{TT} \) scanning over \( \nu \) directions according to MC PDFs

\[ M^2_{\tau\tau} = m_{\text{vis}}^2 + m_{\text{miss}}^2 + 2\sqrt{p_{\text{vis}}^2 + m_{\text{vis}}^2}\sqrt{p_{\text{miss}}^2 + m_{\text{miss}}^2} - 2p_{\text{vis}}p_{\text{miss}} \cos \Delta \theta_{\text{vis,miss}} \]

A. Eilagin et al., NIM A 654 (2011) 481
Backgrounds to $A\rightarrow\tau\tau$

- $Z/\gamma^*\rightarrow\tau\tau$ background estimated from data (all channels)
  - Select $Z/\gamma^*\rightarrow\mu\mu$ and replace the muon response with a tau response from MC
  - Apply selection to the embedded sample
  - Check agreement with $Z/\gamma^*\rightarrow\tau\tau$ simulation

- QCD multijet backgrounds estimated from data (all channels)
  - Data-driven with ABCD method
  - $e\mu$ and $lh$ channels: use SS/OS & lepton isolation
  - $hh$ channel: use SS/OS & tau ID severity

- Other backgrounds
  - Top ($b$-tag samples) from data CR
    - $ll$ and $lh$ channels
  - $W$+jets also from data CR
    - $lh$ channel

\[ n_A = n_B \times \frac{n_C}{n_D} \]
• Event selection
  • Trigger: Single e (20 or 22 GeV) or μ (18 GeV), or combined e+μ (10 GeV and 6 GeV)
  • Exactly one e and opposite signed μ with $E_T$ and $p_T$ on trigger efficiency plateau, $m_{e\mu} > 30$ GeV
  • Events split by jet flavor: 1 b-tag and 0 b-tag
  • Reduce ttbar and diboson backgrounds: MET + $p_T^e + p_T^\mu < 125$ GeV (b-tag) or < 150 GeV (b-veto)
  • $\Delta \phi (e,\mu) > 2.0$ (b-tag) or > 1.6 (b-veto)
  • $\Sigma \cos \Delta \phi (\text{MET, l}) > -0.2$ (b-tag) or > -0.4 (b-veto)
  • b-tag: scalar sum of jets, $H_T < 100$ GeV

• Background estimation
  • Multi-jets: ABCD estimate using e/μ isolation requirements and charge correlation
  • ttbar: Extrapolated from control regions using 2 b-tagged sample
• Event selection
  • Trigger: Single e (20 or 22 GeV) or μ (18 GeV)
  • Exactly one e with $p_T > 25$ GeV or one μ with $p_T > 20$ GeV
  • One $\tau_{had}$ with $E_T > 20$ GeV
  • $m_T (l, MET) < 30$ GeV
  • Split by b-tagging:
    • b-tagged sample: highest $E_T$ jet is b-tagged and has $20 < E_T < 50$ GeV
    • b-vetoed sample: highest $E_T$ jet *not* b-tagged and MET > 20 GeV
• Background estimation
  • Multi-jets: ABCD estimate uses e/μ isolation requirements and charge correlation
  • ttbar: Derive correction factor for simulation using 2-btag selection
A→τ\text{had}τ\text{had}

- Event selection
  - Trigger: Di-τ\text{had} (29 GeV and 20 GeV)
  - Two opposite-sign trigger-matched τ\text{had} candidates. No e nor μ
    - Leading τ\text{had}: E_T > 45 GeV, tight ID
    - 2\text{nd} leading τ\text{had}: E_T > 30 GeV, medium ID
  - MET > 25 GeV
  - Split by b-tagging:
    - b-tagged sample: Highest E_T jet is b-tagged and has 20<E_T<50 GeV
    - b-vetoed sample: Highest E_T jet not b-tagged and MET > 60 GeV
- Background estimation
  - Multi-jets: ABCD estimate uses τ ID requirements and opposite sign/same sign events
  - Tau modeling: Correct simulation using Z→τ\text{had}τ_μ (trigger/ID) and W→μν+jets (jet fake rate)
- Background modeled using smooth functions
- Signal modeled using Breit-Wigner convolved with Gaussian resolution, together with Landau function for low-mass tail
  - BW width fixed to FeynHiggs prediction
Two Higgs Doublet Models (2HDMs)

- Additional Higgs doublet could appear in SUSY or other BSM theories (hierarchy problem, dark matter)
  - Results in 5 Higgs bosons
- Four types (I, II, III, IV) of two Higgs-doublet models satisfy Glashow-Weinberg condition
  - No tree-level flavor changing neutral currents
- Light Higgs couplings are function of two parameters:
  - Mixing angle $\alpha$ between two CP-even states $h, H$
  - Ratio of vacuum expectation values of 2 doublets: $\tan(\beta)=v_2/v_1$
- Assume that observed Higgs boson is the light Higgs, $h$

<table>
<thead>
<tr>
<th>Coupling strength</th>
<th>Type I $\sin(\beta - \alpha)$</th>
<th>Type II $\sin(\beta - \alpha)$</th>
<th>Type III $\sin(\beta - \alpha)$</th>
<th>Type IV $\sin(\beta - \alpha)$</th>
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<td>$\kappa_V$</td>
<td>$\sin(\beta - \alpha)$</td>
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<td>$\kappa_u$</td>
<td>$\cos(\alpha)/\sin(\beta)$</td>
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<td>$\kappa_d$</td>
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Prospects for A->Zh at 14 TeV

- Search for A->Zh->llbb
  - Example signal for $m_A$=360 GeV (top right)
- Expected limit with 14 TeV data (left)
  - Analysis of 8 TeV on-going now – stay tuned!
- Translated into limits on $m_A$ & $\cos(\beta-\alpha)$ in Two-Higgs-Doublet-Model (2HDM) Type II i.e. “MSSM-like” Higgs sector (bottom right)