Experimental Overview of the Exotic h_{125} Decays

B. Kaplan (NYU)

December 4, 2015

Some Musings Before We Begin

A Busy Few Years

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Things to Keep in Mind

- Many signatures have low p_T or highly collimated final states
  - Not always obvious what to trigger on
  - Sometimes difficult to reconstruct final state objects (e.g. hadronic tau ID is spoiled if there is another lepton nearby)
- Recall the coupling limits on BSM decays is O(30%)

$h_{125} \to ZZ_d$ and $Z_d Z_d$: Overview

Submitted to Phys. Rev. D, arXiv:1505.07645 (ATLAS)

- Model-independent search for h_{125} coupling to dark vector boson states
- Focus on $gg \to h_{125}$ and 15 GeV $< m_{Z_d} <$ 60 GeV
- 3 channels: 4μ, $4e$ and $2\mu 2e$
- single and dilepton triggers used
- Muons (electrons) must have $p_T > 6$ GeV (7 GeV) and $|\eta| < 2.7$ (2.47)
- The 3 leading leptons must satisfy $p_T > 20$, 15 and 10 GeV
- Requires a Higgs candidate: 115 GeV $< m_{4\ell} <$ 130 GeV

$h_{125} \to ZZ_d$ and $Z_d Z_d$: Overview cont.

$h_{125} \rightarrow ZZ_d$ and $Z_d Z_d$: Overview cont.

$$h_{125} \rightarrow ZZ_d$$

- m_{12} defined as SFOS pair with mass closest to m_Z
- $50 < m_{12} < 105$ GeV
- Background estimation a mixture of data-driven methods and simulation

$h_{125} \to ZZ_d$ and $Z_d Z_d$: Overview cont.

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- $50 < m_{12} < 105$ GeV
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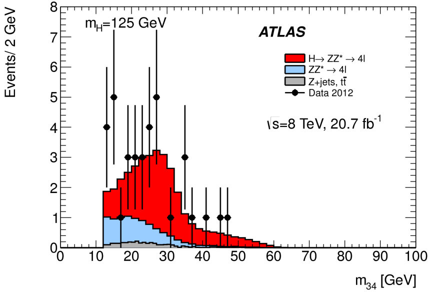
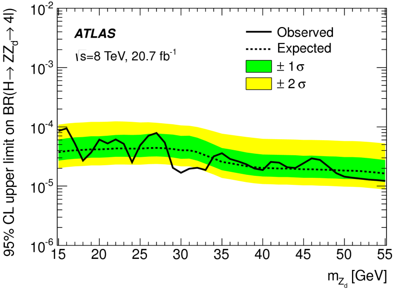
$$h_{125} \to Z_d Z_d$$

- Loose signal region requires $m_{12}, m_{34} < m_h/2$, $m_{12} > m_{34}$
- Tight signal region requires $|\Delta m| < 5, 3, 4.5$ GeV : $4e$,4μ,$2e2\mu$
- Backgrounds from simulation

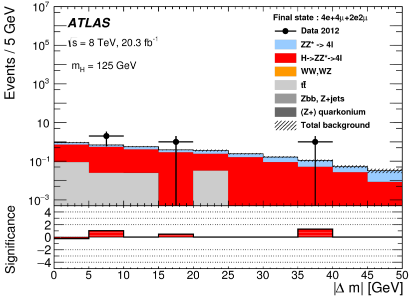
$h_{125} \to ZZ_d$: Results

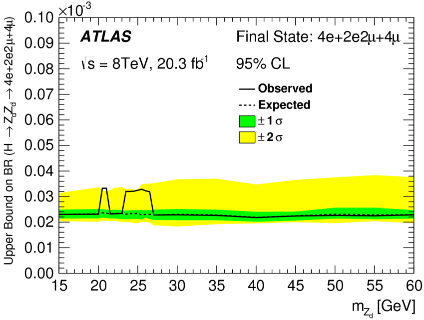




- Limits are determined by fitting the m_{34} distribution to templates
- The signal is modeled as a Gaussian with resolution determined from simulation
- The background templates are determined from simulation

$h_{125} \to Z_d Z_d$: Results





- The $|\Delta m|$ plot is shown for the loose signal region
- Background is < 0.1 event per channel
- 1 event in the $4e$ channel
  with 23.5 GeV $\leq m_{Z_d} \leq$ 26.5 GeV ($|\Delta m| = 6.3$ GeV)
- 1 event in the 4μ channel
  with 20.5 GeV $\leq m_{Z_d} \leq$ 21.0 GeV ($|\Delta m| = 5.2$ GeV)

$h_{125} \to aa$ or $\gamma_d\gamma_d \to 4\mu$: Overview

Submitted to Phys. Lett. B, arXiv:1506.00424 (CMS)

Two interpretations:

1. NMSSM: $h \to aa \to 4\mu$ with $2m_\mu < m_a < 2m_\tau$
2. Dark SUSY: $h \to \chi_1^0\chi_1^0$ with $\chi_1^0 \to \chi_d^0\gamma_d$ and $\gamma_d \to 2\mu$

Event Selection:

- Events collected with a dimuon trigger
- Require at least 4 isolated* μ with $p_T > 8$ GeV and $|\eta| < 2.4$
  scriptsize*The isolation is calculated excluding the muons
- At least one muon with $p_T >$17 GeV and $|\eta| < 0.9$ ($\mu*$)
- SFOS pairs formed with $m_{1\mu\mu}$ always containing $\mu*$
- $m_{1\mu\mu}$ should be close to $m_{2\mu\mu}$
  $|m_{1\mu\mu} - m_{2\mu\mu}| < 0.13$ GeV $+ 0.065$ $(m_{1\mu\mu} + m_{2\mu\mu})/2$

$h_{125} \rightarrow aa$ or $\gamma_d \gamma_d \rightarrow 4\mu$: Overview cont.

- Background is dominated by $b\bar{b}$ production
- The 2D $(m_{1\mu\mu}, m_{2\mu\mu})$ distribution is determined by fitting templates to a data control sample
- Normalization of the $b\bar{b}$ background taken from events where $m_{1\mu\mu}$ is not close to $m_{2\mu\mu}$

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- The sub-dominant J/ψ background is measured in a data control sample, while the small Drell Yan background is taken from simulation

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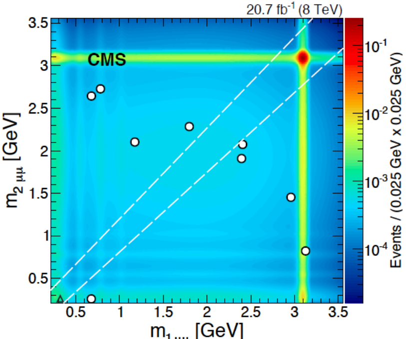
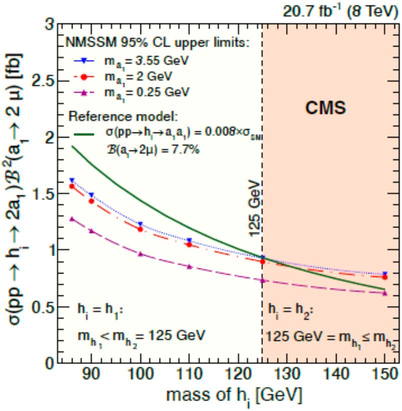
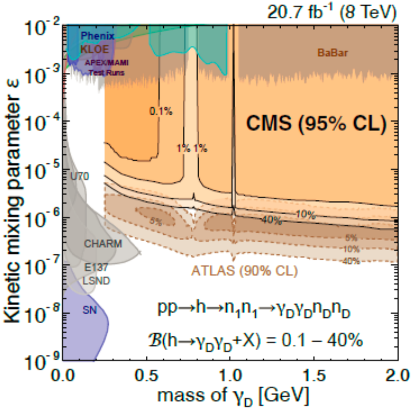


- 1 event (triangle) consistent with signal hypothesis (white lines)
- 9 other events observed
- Colored scale indicates the SM background estimate

$h_{125} \to aa$ or $\gamma_d\gamma_d \to 4\mu$: Results





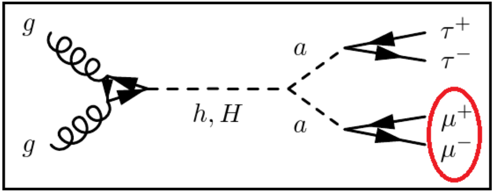
- NMSSM: Limits on BR($h \to aa$) better than 0.8 %
- Dark SUSY: Limits indicated as solid black curves
  $m_{\chi_1^0}$ set to 10 GeV and $m_{\chi_D^0}$ set to 1 GeV
  (ϵ is the kinetic mixing parameter and relates the mass of γ_D its lifetime)

$h_{125} \to aa \to \mu\mu\tau\tau$: Overview

Phys. Rev. D92 (2015) 052002 (ATLAS)

- Interpreted in the context of the NMSSM
- Focus on, i.e. optimize selection for, $2 \cdot m_\tau < m_a < 2 \cdot m_b$
  - Leptons from a decay will be highly collimated
  - Analysis extended above $2 \cdot m_b$ in case couplings to quarks are suppressed
- Coupling related to mass of decay products
  $\Rightarrow$ *large BR($a \to \tau\tau$) at low mass*
- $a \to \mu\mu$ gives a narrow resonance
  $\Rightarrow$ *clean experimental signature*

Analysis Overview ($\mu\mu\tau\tau$)

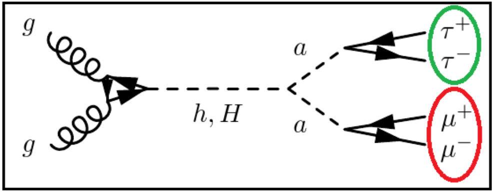


1. Pre-select $\mu^{\pm}\mu^{\mp}$ events

Strategy: Use $a \to \mu\mu$ resonance to perform a bump-hunt

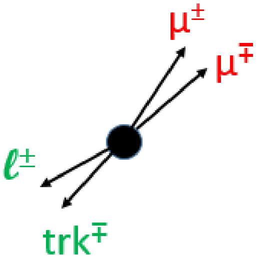
- Use single and dimuon triggers
- Require 2 isolated* muons, with p_T >16 GeV
  *For lower a masses, the muons will be collimated. Correct the isolation variable to account for this
- They must be OS and $p_T(\mu\mu)$ >40 GeV

Analysis Overview ($\mu\mu\tau\tau$)



1. Pre-select $\mu^{\pm}\mu^{\mp}$ events
2. Signal Selection: $\mu^{\pm}\mu^{\mp}+\ell^{\pm}\mathrm{trk}^{\mp}$

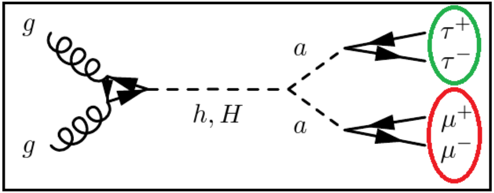
Detector Signature:



Optimize SR for selecting $a \to \tau\tau$

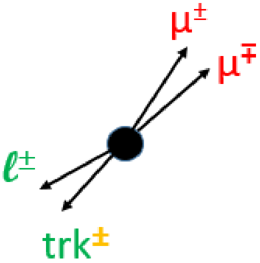
- Best sensitivity found for at least one $\tau \to \ell$
- Other τ decay inclusive
  $\Rightarrow$ Require 1, 2, or 3 nearby tracks
- Lead track carries charge of τ
  $\Rightarrow$ ℓ and leading track are OS
- Two SRs based on ℓ flavor

Analysis Overview ($\mu\mu\tau\tau$)



1. Pre-select $\mu^{\pm}\mu^{\mp}$ events
2. Signal Selection: $\mu^{\pm}\mu^{\mp}+\ell^{\pm}\mathrm{trk}^{\mp}$
3. Validation: $\mu^{\pm}\mu^{\mp}+\ell^{\pm}\mathrm{trk}^{\pm}$

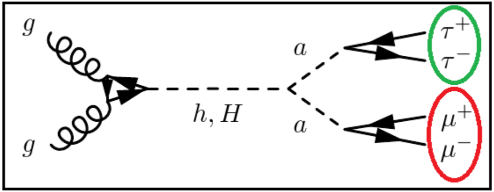
Detector Signature:



Test methods in validation regions

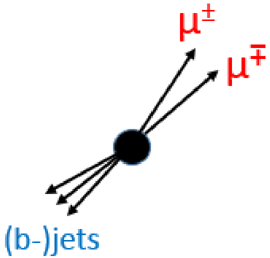
- Invert OS requirement on ℓ and leading track
- Comparable backgrounds, but no signal
- Two VRs based on ℓ flavor

Analysis Overview ($\mu\mu\tau\tau$)



1. Pre-select $\mu^\pm\mu^\mp$ events
2. Signal Selection: $\mu^\pm\mu^\mp + \ell^\pm \mathrm{trk}^\mp$
3. Validation: $\mu^\pm\mu^\mp + \ell^\pm \mathrm{trk}^\pm$
4. Control: $\mu^\pm\mu^\mp$+(b-)jets

Detector Signature:



Measure backgrounds in control regions

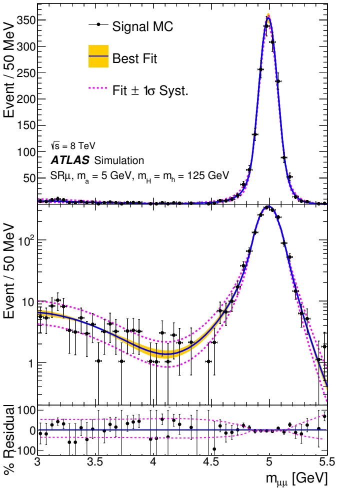
- Replace $\tau\tau$ selection with jets
- Two CRs for light- and heavy- flavor backgrounds

Fitting Strategy ($\mu\mu\tau\tau$)

Perform a bump hunt in $m_{\mu\mu}$ from 3.7 to 50 GeV in SRs

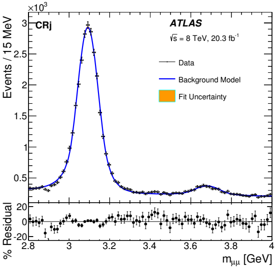
- Background and signal models measured in the data!
- Use simulation to study shapes
- Need a robust background model for entire mass range
  1. Non-resonant background (mainly DY)
  2. $t\bar{t}$ background
  3. SM (J/ψ, Υ, Z)
     - The J/ψ is used to constrain the ψ'
     - The low-end Z tail can be significant above 40 GeV
     - All resonances assumed to have a *narrow width*
- Use a common shape for all narrow $\mu\mu$ resonances

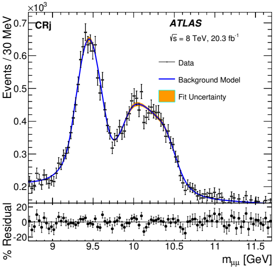
The Narrow $\mu\mu$ Resonances ($\mu\mu\tau\tau$)



$X \to \mu\mu$ Double-Sided Crystal Ball

- Gaussian core, low- and high-end power laws
- 3 free parameters, μ_{CB}, σ_{CB}, α_{CB} *measured in data*
- Mean (μ_{CB}), width (σ_{CB}) linearly depend on m_X
- Tested on 24 signal samples*, varying m_a and m_H
- Fit to SM resonances *in data* shown below

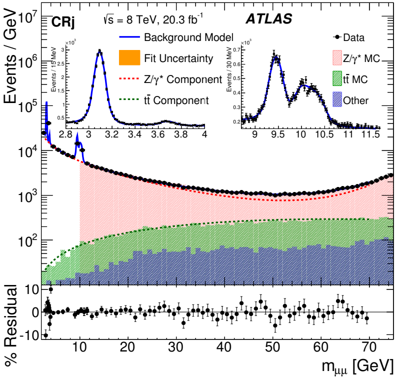




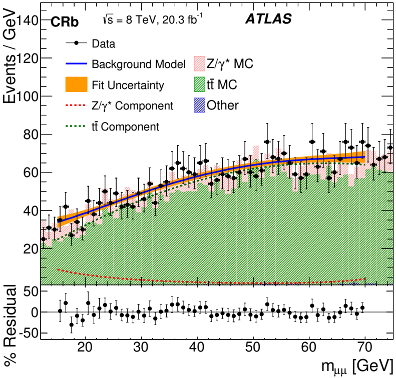
* Details on signal shape (low mass tail and systematics) can be found in the backup

Background Measurement ($\mu\mu\tau\tau$)

CRj: $\tau\tau(\ell + trk) \Rightarrow \geq 1$ jet



CRb: $\tau\tau(\ell + trk) \Rightarrow \geq 2$ b-jets

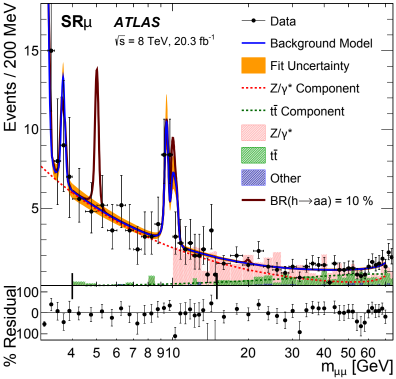


- Results used to constrain fit to SRs

Some details...

- Resonant backgrounds (J/Ψ, ϒ, Z) use a double-sided Crystal Ball
  - Three CB parameters shared with $a \rightarrow \mu\mu$ resonance
- Drell–Yan background modeled by $P_{\gamma^*} = e^{\alpha_{\gamma^*} \cdot m_{\mu\mu}} (m_{\mu\mu})^{n_{\gamma^*}}$
- $t\bar{t}$ modeled by Rayleigh distribution: $P_{tt} = m_{\mu\mu} \times Gaus(m_{\mu\mu}|\mu_{tt} = 0, \sigma_{tt})$

Results: Fit to Signal Region ($\mu\mu\tau\tau$)



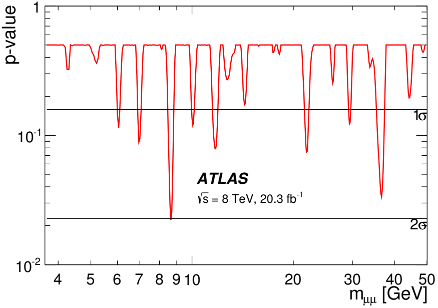
Constrained from Fit to CR

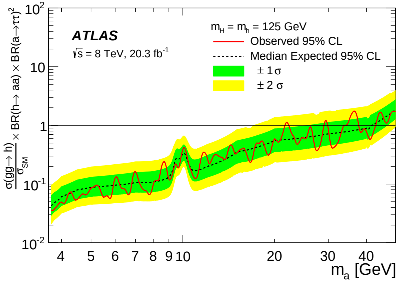
- Background shape parameters (2 for γ^*, 1 for $t\bar{t}$, multiple for SM resonances)
- Relative contributions of higher Ψ and Υ spin states
- Relative contribution of Z to total Z/γ^*

Unconstrained: Relative contributions of Ψ, Υ, $t\bar{t}$ and Z/γ^*

Simulated signal shown in brown for $m_a = 5$, 10 and 20 GeV

Results: Statistical Analysis ($\mu\mu\tau\tau$)





- Observation consistent with SM
- Min p-value $= 0.022$ for $m_{\mu\mu} = 8.65$ GeV
- Global p-value > 0.5
- Upper limit on $BR(h \to aa)$ as low as 3.5% for $m_a = 3.75$ GeV, $m_h = 125$ GeV

$h_{125} \to \phi_1\phi_1 \to 4\tau$: Overview

Submitted to JHEP, arXiv:1510.0634 (CMS)

- Search in interpreted in the context of the NMSSM
- The lightest Higgs boson $\phi_1 = a_1$ or h_1 and $h_{125} = h_1$ or h_2
- The target of the analysis is 4 GeV $< m_{\phi_1} <$ 8 GeV
- The low mass of the ϕ_1 causes the τ's to be collimated

$h_{125} \to \phi_1\phi_1 \to 4\tau$: Analysis Strategy

Event Selection:

- Require at least two $\tau \to \mu + 2\nu$
- Require 2 SS muons
  - greatly reduces the background
  - picks 1 μ from each ϕ_1
- Other τ selected as a single track

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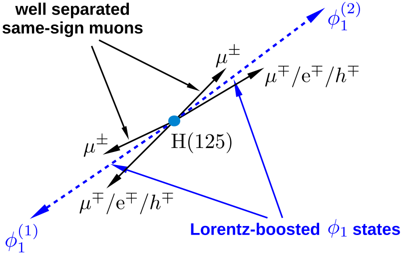

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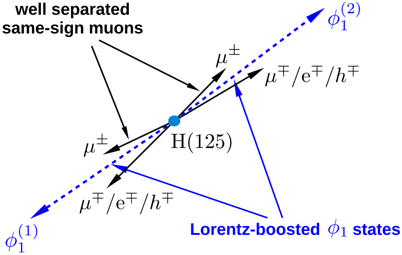
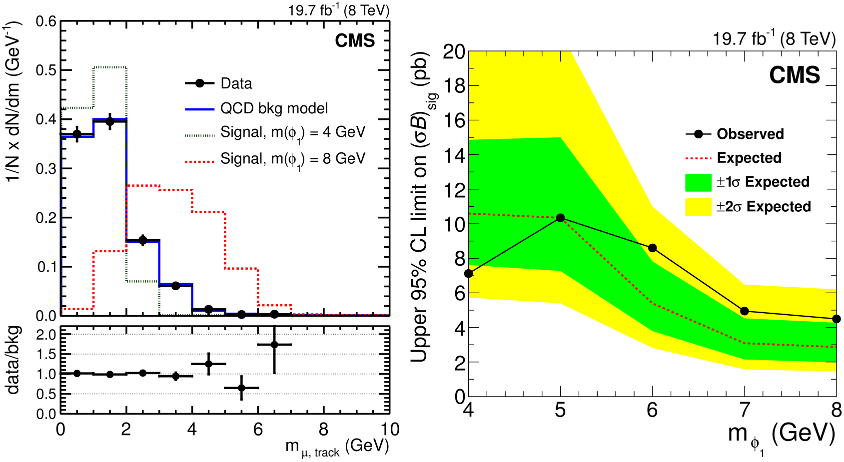


More details:

- A dilepton trigger is used to collect events
- Leading μ $p_T > 17$ GeV, sub-leading with $p_T > 10$ GeV
- Each μ is requried to have exactly 1 track with $p_T > 1$ GeV
- The background shape and normalization determined in data control samples

$h_{125} \to \phi_1\phi_1 \to 4\tau$: Results



- Each event contributes two entries to the left plot
- XS limit corresponds to a BR of 23 to 53% for SM $gg \to h_{125}$

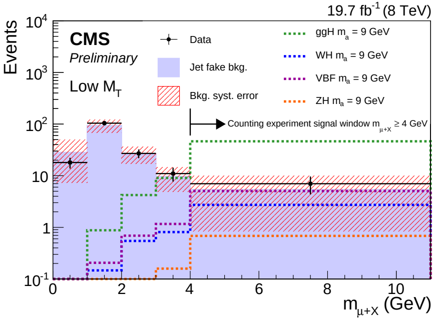
$h_{125} \to \phi_1\phi_1 \to 4\tau$ (V2) : Overview

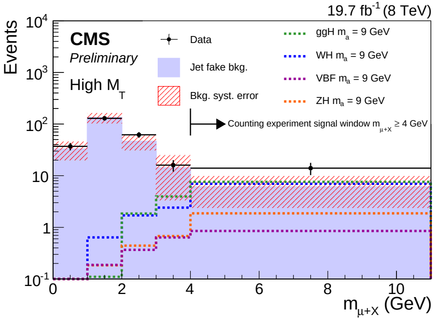
CMS-PAS-HIG-14-022 (CMS Preliminary)

- A second analysis from CMS has recently been made public
- Instead of selecting $\mu +$ track, the τ reconstruction algorithm is modified
  - The jet seed to the algorithm must have a nearby low p_T (> 5 GeV) muon, τ_μ
  - The result of the τ reconstruction is labeled τ_X
  - The ϕ_1 candidate is then the $\tau_\mu\tau_X$ system
- Events are collected with the single muon trigger
  $\Rightarrow$ Events must have a muon with $p_T > 25$ GeV (μ_{trg})
- $M_T(\mu_{trg}, \not{E}_\mathrm{T})$ used to separate Wh production from VBF and $gg \to h$

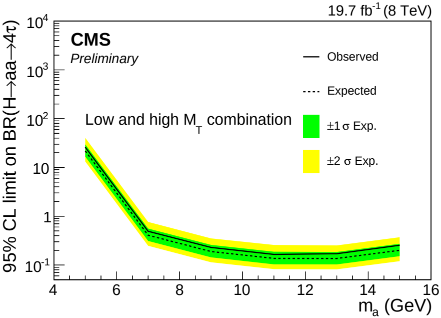
$h_{125} \to \phi_1\phi_1 \to 4\tau$ (V2) : Results

- Backgrounds extrapolated from data control regions





$h_{125} \to \phi_1\phi_1 \to 4\tau$ (V2) : Results



- Strongest limit on BR set at 11 GeV to be 16.5%

$h_{125} \rightarrow aa \rightarrow 4\gamma$: Overview

Submitted to EPJC, arXiv:1509.05051 (ATLAS)

- The paper explores sevral BSM sources of multi-photon events
- For this, talk I'll focus on the NMSSM with $h \rightarrow aa$ and $a \rightarrow \gamma\gamma$
- Considered m_a from 10 to 62 GeV
- Events are reuqired to have at least 3 photons with 2 above 22 GeV and 1 above 17 GeV

$h_{125} \to aa \to 4\gamma$: Overview

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- Events are reuqired to have at least 3 photons with 2 above 22 GeV and 1 above 17 GeV
- At the lower masses, the photons will be collimated, spoiling any isolation requirements

$h_{125} \to aa \to 4\gamma$: Overview

Submitted to EPJC, arXiv:1509.05051 (ATLAS)

- The paper explores sevral BSM sources of multi-photon events
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- This is fixed by removing overlapping photons ($0.15 < \Delta R < 0.4$)

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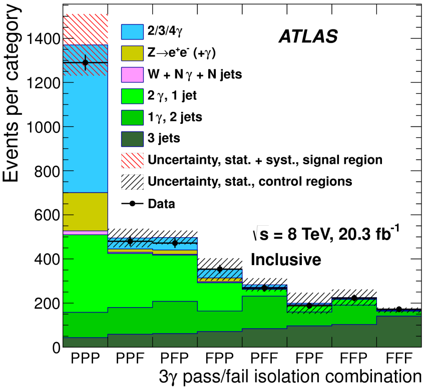
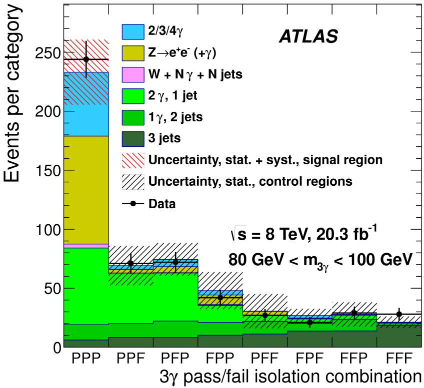
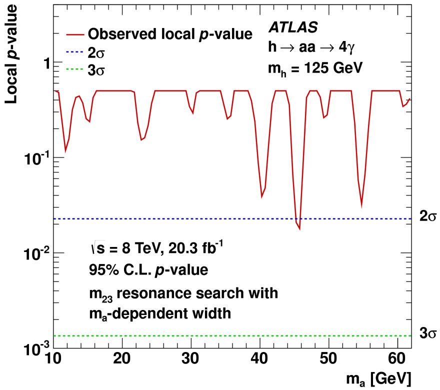
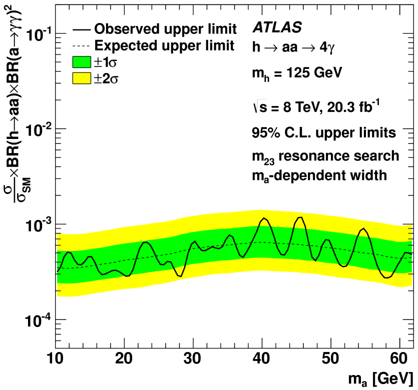




$h_{125} \to aa \to 4\gamma$: Results





- No significant excess is seen across the scanned mass range
- Limits on the BR below 1 pm assuming SM production

Other Interesting Searches

$h_{125} \rightarrow \gamma + \not{E}_{\mathrm{T}}$

1. ATLAS Conference proceedings (ATLAS-CONF-2015-001)
   - GMSB ($h_{125} \rightarrow G\chi_1^0 \rightarrow GG\gamma$ or $h_{125} \rightarrow \chi_1^0\chi_1^0 \rightarrow G\gamma G\gamma$) and NMSSM ($h \rightarrow \chi_2^0\chi_1^0 \rightarrow \chi_1^0\gamma\chi_1^0$ or $h \rightarrow \chi_2^0\chi_2^0 \rightarrow \gamma\chi_1^0\gamma\chi_1^0$)
   - VBF production used to reduce backgrounds
   - 95% C.L. upper limits from 20 to 80% for $\chi_{2(1)}^0$ from 65 to 120 GeV (1γ)
   - 95% C.L. upper limits from 20 to 30% for $\chi_{2(1)}^0$ from 1 to 60 GeV (2γ)
2. CMS Paper (Submitted to Phys. Lett. B, arXiv:1507.00359)
   - GMSB ($h_{125} \rightarrow G\chi_1^0 \rightarrow GG\gamma$)
   - Events for $gg \rightarrow h_{125}$ collected during "data parking" program (7.4 fb^{-1})
   - Full 2012 dataset used for Zh_{125} channel
   - 95% C.L. upper limits from 7 to 13% for χ_1^0 between 1 and 120 GeV

Other Interesting Searches

Displaced Signatures

1. Hidden Valley: $h_{125} \rightarrow \pi_v \pi_v \rightarrow$ displaced jets (ATLAS)
   - Decays in the hadronic calorimeter (Phys. Lett. B 743, 15 (2015))
     Sensitivty to lifetimes from 0.1 to 10 m
   - Decays in the Muon Spectrometer (Submitted to PRD. arXiv:1504.03634))
     Similar range, but more sensitive at longer lifetimes
2. Dark photons: $h_{125} \rightarrow f_d f_d \rightarrow \gamma_d \gamma_d + \not{E}_{\mathrm{T}} \rightarrow$ displaced lepton jets
   - From last pixel layer to the hadronic calorimeter for electrons
   - From last pixel layer to the muon spectrometer for muons
   - Sensitivity to lifetimes from 1 cm to 1 m (JHEP11(2014)088)

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- Need $O(10\text{fb}^{-1})$ to acheive the same sensitivity as Run 1

Stay Tuned for 2016!