Search for di-Higgs final states and rare or exotic decays of the Higgs boson by the ATLAS collaboration

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Topics

1. Searches for (Non-)Resonant Higgs Production

   - $(X \rightarrow) hh \rightarrow \gamma\gamma bb$: non-resonant and resonant production
     Narrow Higgs, m_X: 275-400 GeV
     (ATLAS-CONF-2016-004)

   - $X \rightarrow hh \rightarrow bbbb$: resonant production
     Narrow Higgs and Kaluza-Klein graviton, m_X: 600-3000 GeV
     (ATLAS-CONF-2016-017)

2. Exotic/Rare Higgs Decays

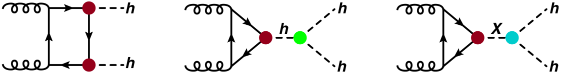
   - $H \rightarrow e\tau$ and $H \rightarrow \mu\tau$ (LFV)
     (arXiv:1508.03372)

Dataset

- Di-Higgs analyses use 3.2 fb^{-1} of pp data collected in 2015, w/ $\sqrt{s} = 13\,TeV$
- LFV analysis uses 20.3 fb^{-1} of pp data collected in 2012, w/ $\sqrt{s} = 8\,TeV$

$hh \to \gamma\gamma bb$ (ATLAS-CONF-2016-004)

Search for non-resonant and resonant $(X \to)$ hh production



- Overview
  - Signal region (SR) with 2 photons and 2 b-tagged jets
  - Control region (CR) with 2 photons and 0 b-tagged jets
  - 105 GeV $< m_{\gamma\gamma} <$ 160 GeV, 95 GeV $< m_{b\bar{b}} <$ 135 GeV
  - $|m_{\gamma\gamma} - m_H| < 2 \cdot \sigma_{m_{\gamma\gamma}} = 3.1$ GeV (res. only)
  - m_X dependent cut on $m_{bb\gamma\gamma}$ (res. only),
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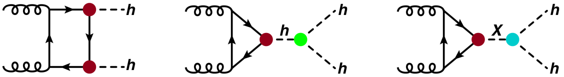

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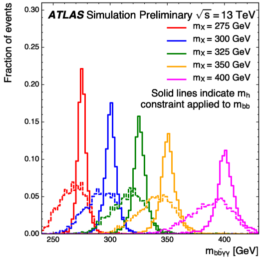
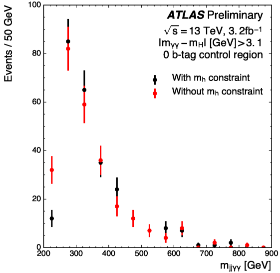
- The $h \to bb$ Hypothesis
  - 4-momentum of $b\bar{b}$ system scaled by $m_h/m_{b\bar{b}}$
  - 60% improvement, for sim. samples, in $m_{b\bar{b}\gamma\gamma}$ res. (top)
  - No significant impact on background (bottom)





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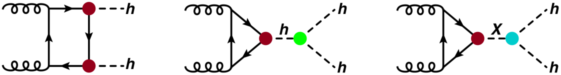
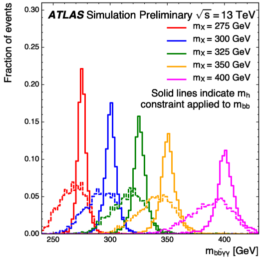
Search for non-resonant and resonant ($X \to$) hh production





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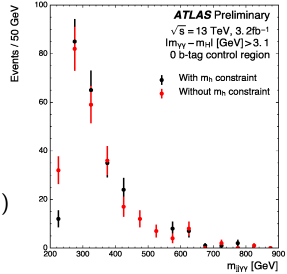


- The $h \to bb$ Hypothesis
  - 4-momentum of $b\bar{b}$ system scaled by $m_h/m_{b\bar{b}}$
  - 60% improvement, for sim. samples, in $m_{b\bar{b}\gamma\gamma}$ res. (top)
  - No significant impact on background (bottom)
- Statistical Method

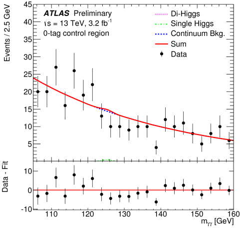
Non-Res.: Unbinned $m_{\gamma\gamma}$ spectrum fit to background (exponential) and signal (double-sided Crystal Ball) models

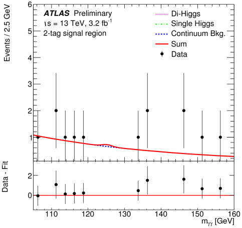
Res.: "Cut-and-count" in signal region

- Background is extrapolated from $m_{\gamma\gamma}$ sidebands and CR

$hh \to \gamma\gamma bb$: Results

- 0 events observed in signal region

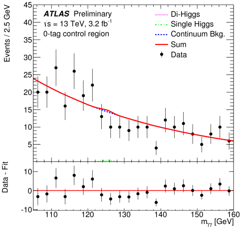


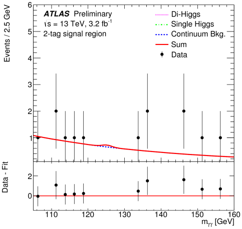


$hh \to \gamma\gamma bb$: Results

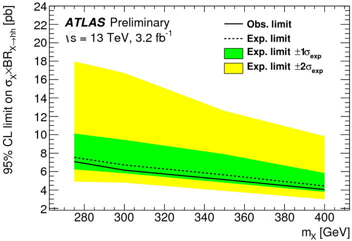
- 0 events observed in signal region
- Upper limit of 3.9 pb on non-resonant hh production set at the 95% C.L.
- Upper limits set vs. m_X on $\sigma_X \times BR_{X\to hh}$ (left) and converted to the event yield from $X \to hh$ (right)

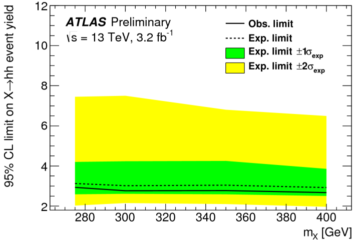
Limits based on an effective field theory (EFT) model implemented in MadGraph5_aMC@NLO v2.2.2





Resonant





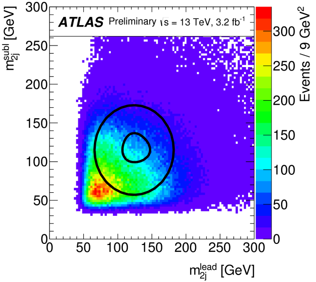
$X \rightarrow hh \rightarrow bbbb$ (ATLAS-CONF-2016-017)

Analysis divided into 'resolved' and 'merged' regimes:

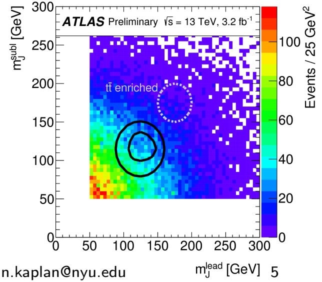
- Resolved Overview
  - m_{G^*} is 'small' (below 1.1 TeV) $\Rightarrow$ 4 b-tagged jets
  - Di-jet (jj) systems are formed, such that $\Delta R_{jj} < 1.5$
  - 2 jj's are required to be consistent with m_h (inner circle)
  - Dominant multi-jet background determined in 2-tag data, corrected w/ 'outer area' and validated in 'annulus'
- Merged Overview
  - m_{G^*} is 'large' $\Rightarrow$ h is 'boosted' $\Rightarrow$ b-jets are collimated
  - Select 2 jets with R=1.0 (J), and $|\Delta\eta_{JJ}| < 1.7$
  - Divide events by number of b-tagged track jets
  - 2 J's are required to be consistent with m_h (inner circle)
  - Two signal regions: '3-tag' and '4-tag'
  - Again, multi-jet background determined in 2-tag data, corrected w/ 'outer area' and validated in 'annulus'

Note: O(5-10%) background from $t\bar{t}$ discussed in backup

Resolved ('2-tag'):



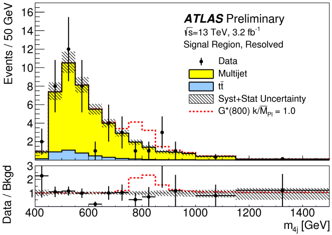
Merged ('2-tag'):



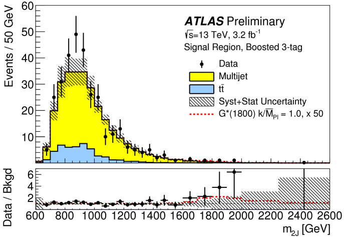
$X \to hh \to bbbb$: Results

- No deviation from SM seen in signal regions

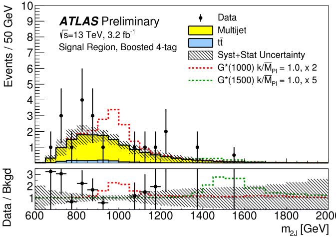
Resolved:



Merged ('3-tag'):



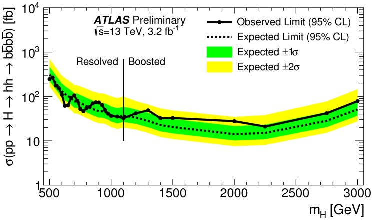
Merged ('4-tag'):



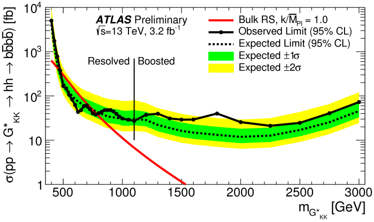
$X \to hh \to bbbb$: Results

- No deviation from SM seen in signal regions
- 95% C.L. upper limits are placed vs. the mass of X
- Results interpreted for a narrow $H \to hh$ as well as for G^*_{KK}
- A non-resonant interpretation yields a 95% C.L. upper limit on $\sigma(pp \to hh \to b\bar{b}b\bar{b}) = 1.22$ pb

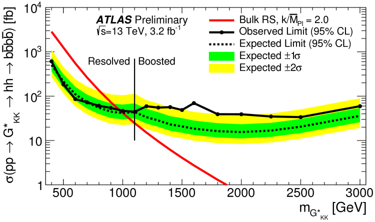
Narrow H:



G^*_{KK} $(k/\bar{M}_{Pl} = 1)$:



G^*_{KK} $(k/\bar{M}_{Pl} = 2)$:



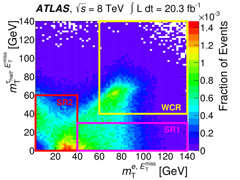
The transition mass was chosen such that the expected limits intersect.

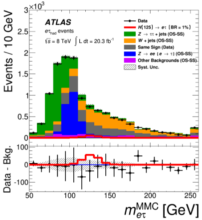
LFV Higgs Decays (arXiv:1508.03372)

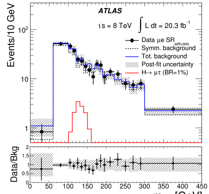
- Overview
  - Combines 4 channels: $(e\tau, \mu\tau) \otimes (\tau_{lep}, \tau_{had})$
  - $\mu\tau_{had}$ channel taken from JHEP11(2015)211
- τ_{had} Channels
  - Exactly 1 e or μ and 1, OS τ_{had} candidate
  - $m_T^{\ell,\ \not{E}_T}$ used as primary discriminants
  - Missing Mass Calculator (MMC) used to reproduce m_h

    The MMC uses a likelihood fit, using the $m_{\tau_{had}} = m_{tau}$ hypothesis
  - $t\bar{t}$ background estimated using events w/ 2 b-tagged jets
  - Multi-jet events estimated using SS leptons
- τ_{lep} Channels
  - Exactly 1 e and 1 OS μ
  - $\Delta\phi$ between leptons and $\not{E}_T$used to increase sensitivity
  - Signal regions defined w/ and w/out jets
  - Primary discriminant is collinear mass:

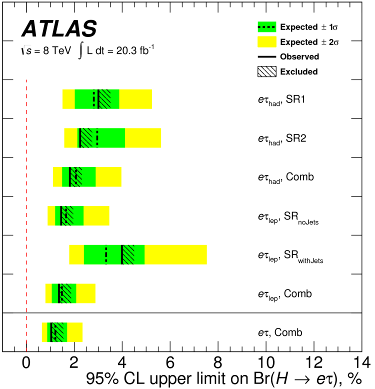
    $$m_{coll} = \sqrt{2p_T^{\ell_1}\left(p_T^{\ell_2} + \not{E}_T\right)(\cosh\Delta\eta - \cos\Delta\phi)}$$
  - Bkg. estimation uses the symmetry of the $e\mu$ final state:
    - $e\mu$ is background for μe and $\leftrightarrow$

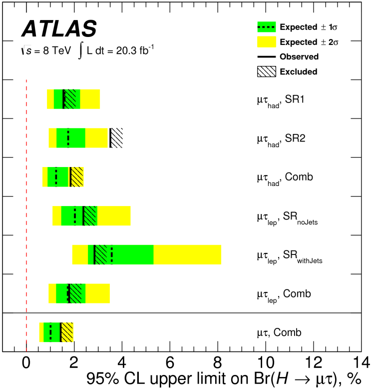






LFV Higgs Decays: Results





- Observed 95% C.L. upper limits on LFV Higgs decays O(1-2%)
- 1σ excess in $\mu\tau$ (bottom right) driven by 1.3σ excess in $\mu\tau_{had}$ (3^{rd} right)
    - Best fit $BR(H \to \mu\tau) = (0.53 \pm 0.51)\%$

Concluding Thoughts

- We have had a very successful BSM physics program in the first year of Run 2
  - Some interesting Run1 results still appearing
- The next year promises to be very exciting
  - The projected 25 fb^{-1} for 2016 opens up sensitivity to many more avenues for discovery


Stay
Tuned!

Backup Slides

$\gamma\gamma bb$ Background Extrapolation

$$N^B_{SR} = N_{SB}\frac{\varepsilon^B_{m_{\gamma\gamma}}}{1-\varepsilon^B_{m_{\gamma\gamma}}}\varepsilon^B_{m_{b\bar{b}\gamma\gamma}},$$

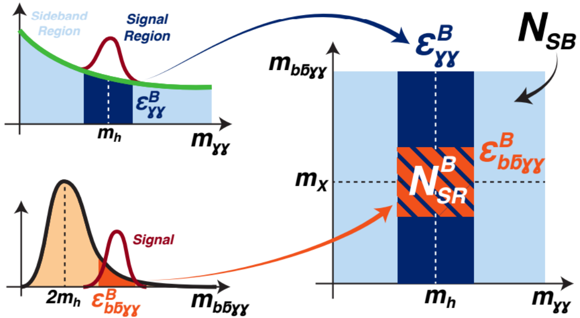


Figure 3: The search for the resonant di-Higgs production requires additional selection on the $m_{\gamma\gamma}$ and $m_{b\bar{b}\gamma\gamma}$ distributions. Two counting categories are defined - a background-dominated category from the $m_{\gamma\gamma}$ sidebands, and a signal region, inside the $m_{\gamma\gamma}$ and $m_{b\bar{b}\gamma\gamma}$ windows. One factor is required in each dimension to extrapolate the background rate from the sideband to the signal region. Here, N_{SB} refers to the observed number of sideband events from the continuum background, and N^B_{SR} refers to the expected number of continuum background events in the signal region. The two ε values are the efficiencies to pass the cuts on $m_{\gamma\gamma}$ and $m_{b\bar{b}\gamma\gamma}$.

$\gamma\gamma bb$ Systematics

Source of systematic uncertainty		Impact in % on the search for di-Higgs production in non-resonant mode			resonant mode		
		hh signal	Single-h bkg	Cont.	$X\to hh$ signal	SM h+hh bkg	Cont.
Luminosity		±5.0	±5.0	-	±5.0	±5.0	-
Trigger		±0.4	±0.4	-	±0.4	±0.4	-
Pileup reweighting		±1.6	+2.4 / −0.4	-	±1.0	±2.3	-
Generated event statistics		±1.3	±16.8	-	±4.3	±12.6	-
Photon	energy resolution	+30 / −15	+30 / −15	-	+7.0 / −0.3	+0.0 / −3.8	-
	energy scale	±0.5	±0.5	-	+1.9 / −3.5	+2.8 / −3.0	-
	identification	±2.5	±2.5	-	±2.5	±2.5	-
	isolation	±3.4	±3.4	-	±3.9	±3.9	-
Jet	energy resolution	±2.7	±24	-	±9.1	±1.6–9.8	-
	energy scale	+1.3 / −1.1	±12	-	±12.1	±10.6	-
b-tagging	b-jets	±12.9	±10.0	-	±12.6	±12.6	-
	c-jets	±0.05	±4.1	-	±0.2	±3.0	-
	light-jets	±0.5	+3.9 / −4.6	-	±0.2	±0.5	-
	extrapolation	±5.1	±2.8	-	±5.2	±3.0	-
Shape	$m_{\gamma\gamma}$ modelling	-	-	±11	-	-	±11
	$m_{b\bar{b}\gamma\gamma}$ modelling	-	-	-	-	±25.0	±27–40
Theory	PDF+α_S	-	+6.8 / −6.6	-	-	+7.4 / −7.3	-
	Scale	-	+5.7 / −8.2	-	-	+6.9 / −10.9	-
	EFT	-	-	-	-	±5.7	-
Total		+34 / −22	+43 / −35	±11	+23 / −22	+36 / −35	±29–41

Table 2: Summary of systematic uncertainties, in percent, for 2-tag events in the signal region. Entries marked '-' indicate that the systematic is not applicable in this category. The luminosity uncertainty is fully correlated across all samples. The jet energy scale uncertainty includes components from various sources, including uncertainties on jets arising from b-quarks. The b-tagging uncertainties include those from the efficiencies to correctly tag jets arising from b-quarks as well as mistagging jets from c-quarks and light-flavour quarks. There are two extrapolation uncertainties in b-tagging: one is from the extrapolation to high-p_T (p_T >300 GeV) jets and one is from extrapolating c-jets to τ-jets. In the table these are combined, although they are treated as independent nuisance parameters in the fit. In the search for $X\to hh$, the jet energy resolution and $m_{b\bar{b}\gamma\gamma}$ modelling uncertainties are parametrised in terms of the mass of the resonance, hence the full range of values is quoted.

The Double Sided Crystal Ball

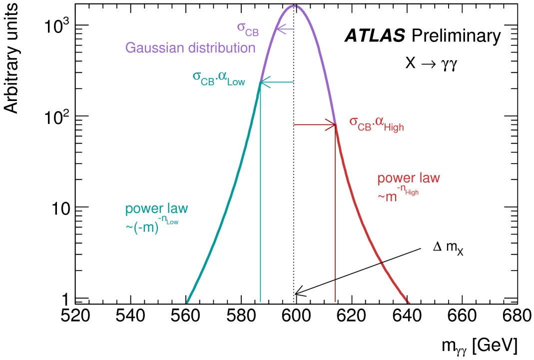


Figure: Description of the double-sided Crystal Ball function parameters: $\Delta m_X = m_X - \mu_{CB}$, where μ_{CB} is the peak of the Gaussian distribution, σ_{CB} represents the width of the Gaussian part of the function, α_{Low} (α_{High}) is the point where the Gaussian becomes a power law on the low (high) mass side, n_{Low} (n_{High}) is the exponent of this power law. (ATLAS-CONF-2014-031)

bbbb Resolved Jet Selection

$$p_{\mathrm{T}}^{\mathrm{lead}} > \begin{cases} 400 \text{ GeV} & \text{if } \mathrm{m_{4j}} > 910 \text{ GeV}, \\ 200 \text{ GeV} & \text{if } \mathrm{m_{4j}} < 600 \text{ GeV}, \\ 0.65 m_{4\mathrm{j}} - 190 \text{ GeV} & \text{otherwise}, \end{cases}$$

$$p_{\mathrm{T}}^{\mathrm{subl}} > \begin{cases} 260 \text{ GeV} & \text{if } \mathrm{m_{4j}} > 990 \text{ GeV}, \\ 150 \text{ GeV} & \text{if } \mathrm{m_{4j}} < 520 \text{ GeV}, \\ 0.23 m_{4\mathrm{j}} + 30 \text{ GeV} & \text{otherwise}, \end{cases}$$

$$\left|\Delta\eta_{\mathrm{dijets}}\right| < \begin{cases} 1.0 & \text{if } \mathrm{m_{4j}} < 820 \text{ GeV}, \\ 1.6 \times 10^{-3} m_{4\mathrm{j}} - 0.28 & \text{otherwise}. \end{cases}$$

$bbbb$ $t\bar{t}$ Background Estimation

Resolved

- Extra jets in the event are used to reconstruct W and t candidates

$$X_{tt} = \sqrt{\left(\frac{m_W - 80.4\,\mathrm{GeV}}{0.1\,m_W}\right)^2 + \left(\frac{m_t - 172.5\,\mathrm{GeV}}{0.1\,m_t}\right)^2},$$

- The $t\bar{t}$ CR has $X_{t\bar{t}} < 3.2$, and the SR has the inverse

Merged

- Strict cuts on the leading J p_T significantly reduces $t\bar{t}$ background
- Remaining background estimated from MC simulation

bbbb Systematics

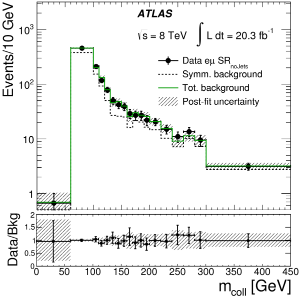
Source	Background	SM hh	G^*_{KK} (500 GeV) $\frac{k}{\bar{M}_{Pl}} = 1$	G^*_{KK} (800 GeV) $\frac{k}{\bar{M}_{Pl}} = 1$	$\frac{k}{\bar{M}_{Pl}} = 2$	H
Luminosity	–	5	5	5	5	5
JER	–	2	3	3	3	4
JES	–	12	14	5	4	6
b-tagging	–	18	15	26	27	26
Theoretical	–	13	2	3	3	3
Multijet	5	–	–	–	–	–
$t\bar{t}$	6	–	–	–	–	–
Total	8	26	21	28	28	28

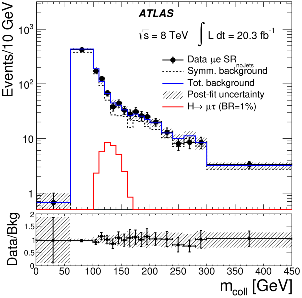
Table 2: Summary of systematic uncertainties (expressed in percentage yield) in the total background and signal event yields in the signal region of the resolved analysis. Signal yield uncertainties are provided for non-resonant SM Higgs pair production, for the G^*_{KK} with $k/\bar{M}_{Pl} = 1$ and $m = 500$ GeV, and for three resonances with $m = 800$ GeV, a G^*_{KK} with $k/\bar{M}_{Pl} = 1$, a G^*_{KK} with $k/\bar{M}_{Pl} =2$, and a spin-0 narrow-width H boson.

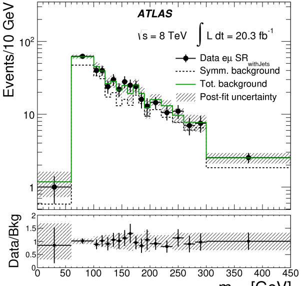
Source	Background	G^*_{KK} $k/\bar{M}_{Pl} = 1$	$k/\bar{M}_{Pl} = 2$	H
Luminosity	-	5.0	5.0	5.0
3-tag				
JER	< 1	< 1	< 1	< 1
JES	2	< 1	< 1	< 1
JMR	1	12	12	11
JMS	5	14	13	17
b-tagging	1	23	22	23
Theoretical	-	3	3	3
Multijet Normalization	3	-	-	-
Statistical	2	1	1	1
Total	7	31	30	33
4-tag				
JER	< 1	< 1	< 1	< 1
JES	< 1	< 1	< 1	< 1
JMR	4	12	13	13
JMS	5	13	13	14
b-tagging	2	36	36	36
Theoretical	-	3	3	3
Multijet Normalization	14	-	-	-
Statistical	3	1	1	1
Total	15	42	42	43

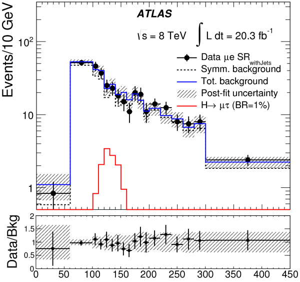
Table 5: Summary of systematic uncertainties (expressed in percentage yield) in the total background and signal event yields in the 3-tag and 4-tag signal regions in the boosted analysis. Uncertainties are provided for a resonance mass of 1.5 TeV in the context of the bulk RS model with $k/\bar{M}_{Pl} = 1$ or 2, as well as for a spin-0 narrow-width H boson. The statistical uncertainties on the background include the fitted $t\bar{t}$ normalization uncertainties and the statistical uncertainty associated with the data yield in the 2-tag sample.

LFV τ_{lep} Fits

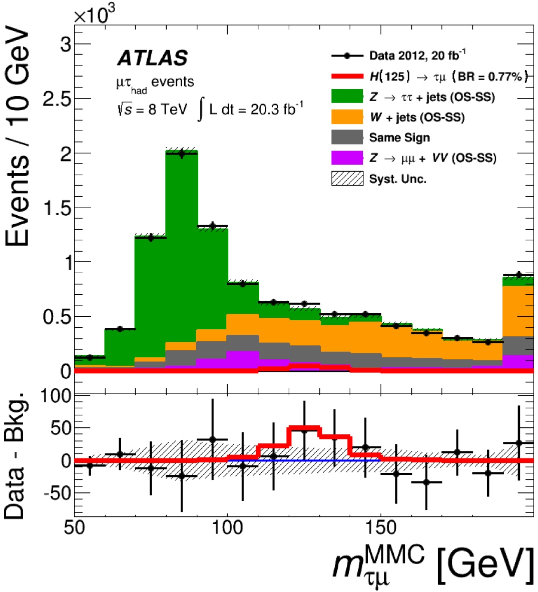








LFV 'excess'


ATLAS
μτ_had events
√s = 8 TeV ∫ L dt = 20.3 fb-1
Data 2012, 20 fb-1
H(125) → τμ (BR = 0.77%)
Z → ττ + jets (OS-SS)
W + jets (OS-SS)
Same Sign
Z → μμ + VV (OS-SS)
Syst. Unc.
×10^3
Events / 10 GeV
Data - Bkg.
m_τμ^MMC [GeV]