hh→$\gamma\gamma$bb Run 1 results from ATLAS and Run 2 prospects

Questions for theorist colleagues

JAA on behalf of ATLAS

Two (related) analyses from ATLAS

- Non-resonant analysis:
  - Require two b-tagged jets with mass loosely consistent with Higgs mass
  - Then require two high-p_T photons, and do bump-hunting in Higgs mass window
  - Continuum shape from < 2 tag events, normalization from sideband
  - Single Higgs background from simulation
  - Use unbinned likelihood fit
- Resonant analysis (focus on < 450 GeV, where 4b dominates)
  - Build off of resonant result, but instead of unbinned S+B fit, perform counting experiment
  - Continuum estimate starts number of events in diphoton mass window (from sideband fit). The efficiency for these events to pass an additional $m_{\gamma\gamma bb}$ mass cut comes again from events with < 2 tags

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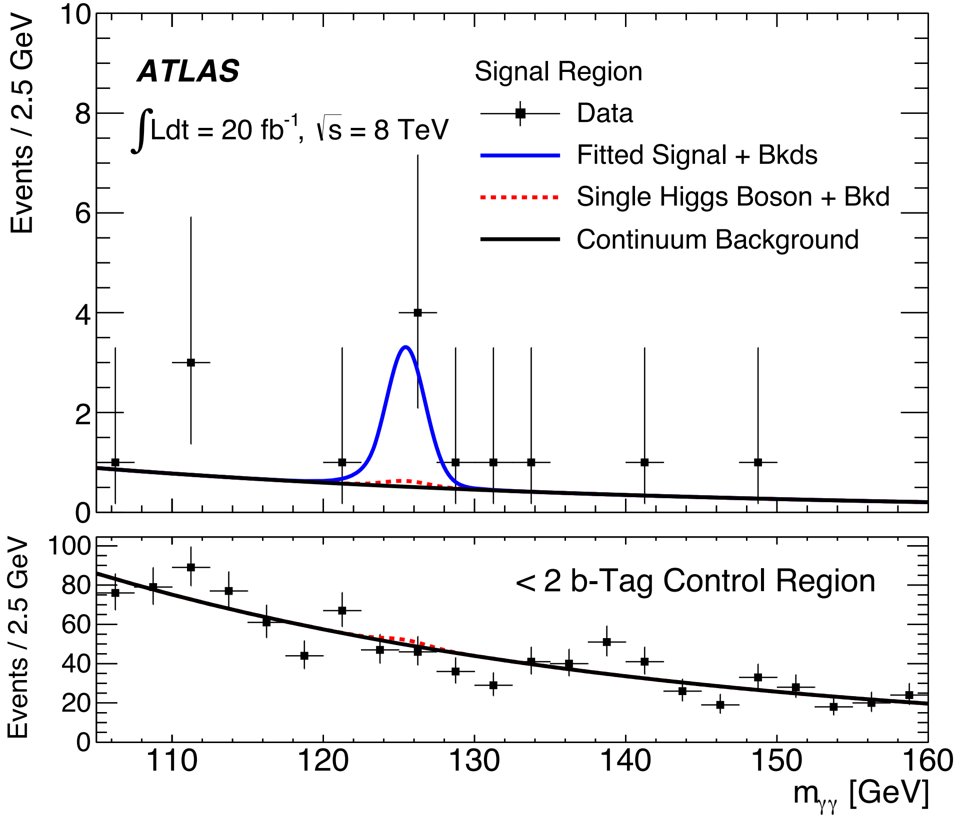
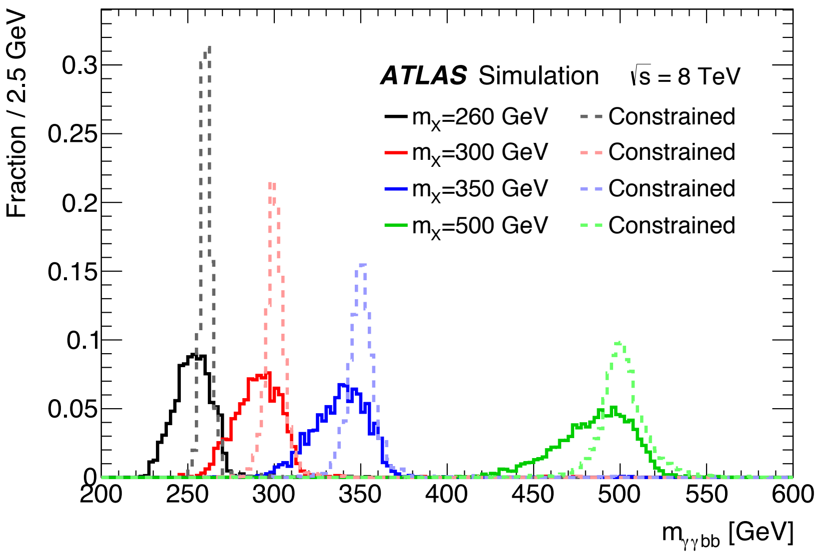


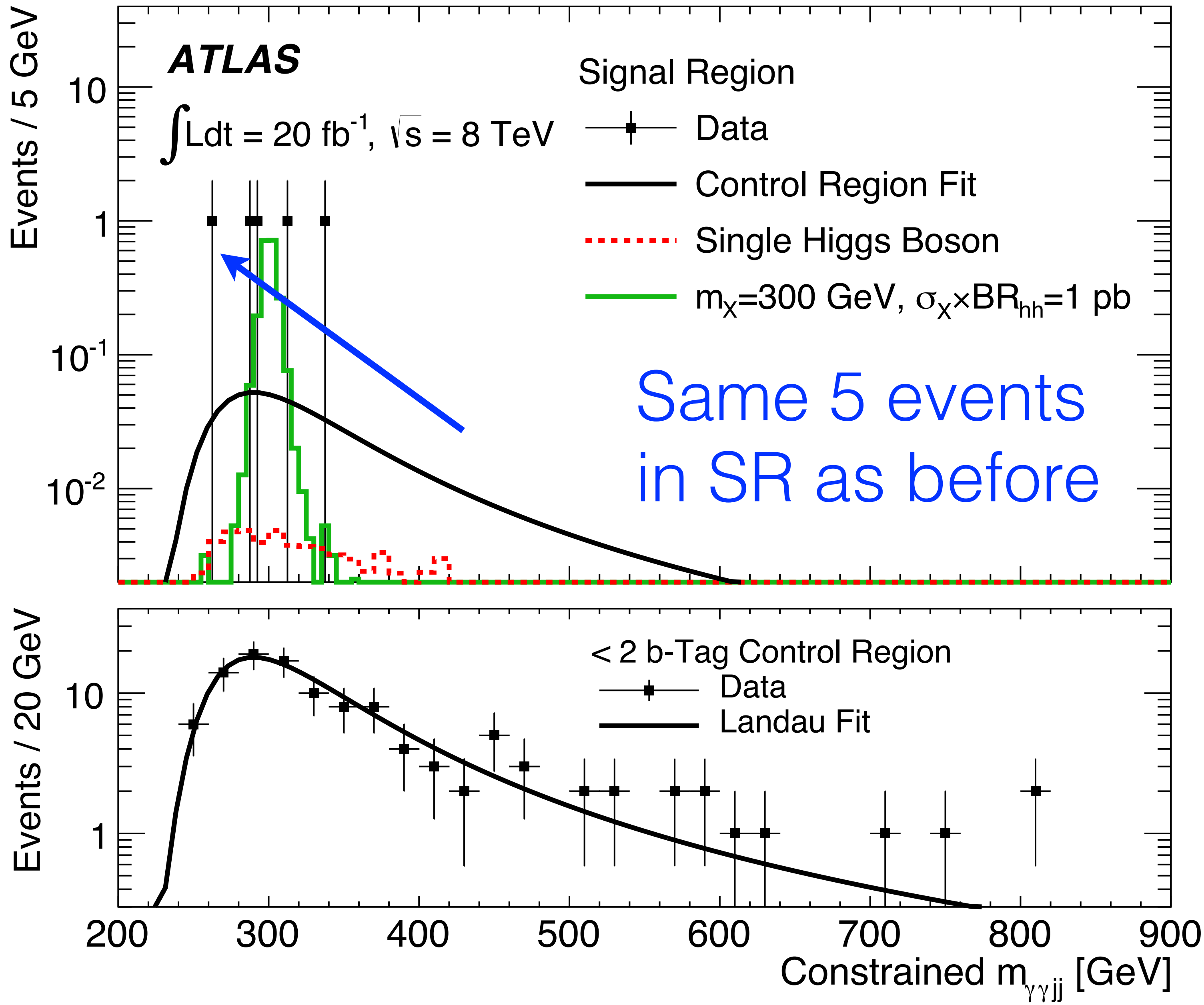
- Set 95% CL upper limit on non-resonant production of 2.2 pb (expected limit 1.0 pb)
- p-value for consistency with background-only hypothesis: 2.4σ
- 5 events observed, 1.3 from continuum, 0.2 from single higgs processes

Process	Fraction of total
ggH	11%
qqH	2%
WH	1%
ZH	17%
$t\bar{t}H$	69%
Total	0.17 ± 0.04 Events

Improving the 4-object mass

- Tagged jets are nominal ATLAS anti-k_T R=0.4 jets with muon 4-vectors added to jet
  - This does not account for spectral effects, nor escaping neutrinos
- Apply simple scaling of bb 4-vector by 125 GeV/m_{bb} before adding to the diphoton 4-vector to form $m_{\gamma\gamma bb}$
  - Gains quite a bit in resolution without significantly sculpting the background
- Considered using instead mass difference between bb and diphoton systems, but less intuitive, and does not perform as well
- Investigating kinematic fits for Run 2
  - Not clear that it gains much




ATLAS
$\int Ldt = 20\ fb^{-1}$, $\sqrt{s} = 8$ TeV
Signal Region
Data
Control Region Fit
Single Higgs Boson
m_X=300 GeV, $\sigma_X \times BR_{hh}$=1 pb
Same 5 events in SR as before
Events / 5 GeV
< 2 b-Tag Control Region
Data
Landau Fit
Events / 20 GeV
Constrained $m_{\gamma\gamma jj}$ [GeV]
200
300
400
500
600
700
800
900

- Run 1: Madgraph5 + Pythia8, two types
  - Non-resonant production (SM LO)
  - Resonant production (gg-initiated Madgraph) spin-0 resonance with ~zero width
  - **Given the expected SM signal (0.04 events), are we sensitive to uncertainties on SM hh process?**
    - **ggF/VBF + heavy flavor uncertainties, too?**

Signal simulation Run 2

- Run 2: Should we consider moving to NLO versions?
  - **Non-resonant production with aMC@NLO (not just gg fusion)? k-factors are flat. How necessary are there?**
  - **Kinematics change quite a bit if Higgs self-coupling varies. Any specific range of interest?**
  - Looking also at composite Higgs (similar kinematics to SM?)
  - **Other non-resonant benchmarks?**
  - Focus on specific production mechanics (long-term)?
- Resonant production
  - 2HDM benchmark was adequate, but try a more exhaustive scan in 2HDM space
  - Focus on lower masses
  - **What widths should we consider? Any specific production mechanics?**
  - **Beyond 2HDM and gravitons, other benchmark models?**

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- Sideband-driven for main backgrounds
- Still useful to understand composition of background. Studies show it's dominated by $\gamma\gamma$jj, γjjj
  - Tight generator cuts on jets and dijet masses close our selection
  - Separate samples with j==b, find that light j, b and c all contribute
  - EW processes tiny, 10% from ttbar (electrons faking photons)
  - 100% uncertainties on SM gg and VBF fusion with heavy flavor (similar to ttH diphoton analyses)

- Similar approach to Run 1 with larger-size photon+jet samples
  - Necessary for better optimization of analysis (ideally never use sidebands due to statistical fluctuations)
- Work towards NLO diphoton+(di)jet samples with heavy flavor (aMC@NLO_MG5?)
  - **What do k-factors look like? How do they change across those samples? How do they vary with kinematics? Would be very useful to have this information**

Expected results with 5 fb^{-1} @ 13 TeV

- Non-resonant signal xsec goes up with factor of 3.4x, so with 6 fb^{-1} we expect same signal yields as 8 TeV data set
- Background will go up too, but we should also optimize cuts a bit better, so expect to have competitive limits with Run 1

Comparing ATLAS and CMS

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	ATLAS	CMS (CMS-PAS-HIG-13-032)
Jet p_T	55/35 GeV	25 GeV
Tag requirement	≥ 2tag	Separate 1tag and ≥2tag regions for signal
m_{jj} range	95-135 GeV	85-155 GeV
m_{jj} method	4-vector scaling	Kinematic fit
Resonance limit method	Counting experiment	Sideband fit
Non-resonance limit	Yes	No
Signal at 300 GeV	CMS ~50% larger in 2-tag channel	
Background at 300 GeV	CMS ~400% larger in 2-tag channel	
Limit at 300 GeV	CMS ~50% better (expected)	

Thank you!

Backup

All small compared to statistical uncertainties

Systematic uncertainty		Non-Resonance Analysis		
		Single h Bkgd	hh Signal	Continuum
Trigger	[%]	0.5		–
Luminosity	[%]	2.8		–
Photon	Identification [%]	2.4		–
	Isolation [%]	2		–
Mass	Resolution [%]	Resolution: 13		–
	Position	Value: +0.5/-0.6 GeV		–
Shape	$m_{\gamma\gamma}$ Continuum Shape [%]	–		11
	$m_{\gamma\gamma b\bar{b}}$: Statistical [%]	–		–
	$m_{\gamma\gamma b\bar{b}}$: jj vs bb [%]	–		–
	$m_{\gamma\gamma b\bar{b}}$: Fit Model [%]	–		–
Jets	b-Tagging [%]	3.3	1.8	–
	Energy Scale [%]	6.5	1.4	–
	b-jet Energy Scale [%]	2.6	0.3	–
	Energy Resolution [%]	4.8	6.3	–
Theory	PDF+Scale [%]	8.4	–	–
	Single h+HF [%]	14	–	–

Fit sidebands to 0-tag data, 1-tag, data with non-isolated photons, and using flat function (largest=11%)

100% uncertainty on gg and VBF due to HF content

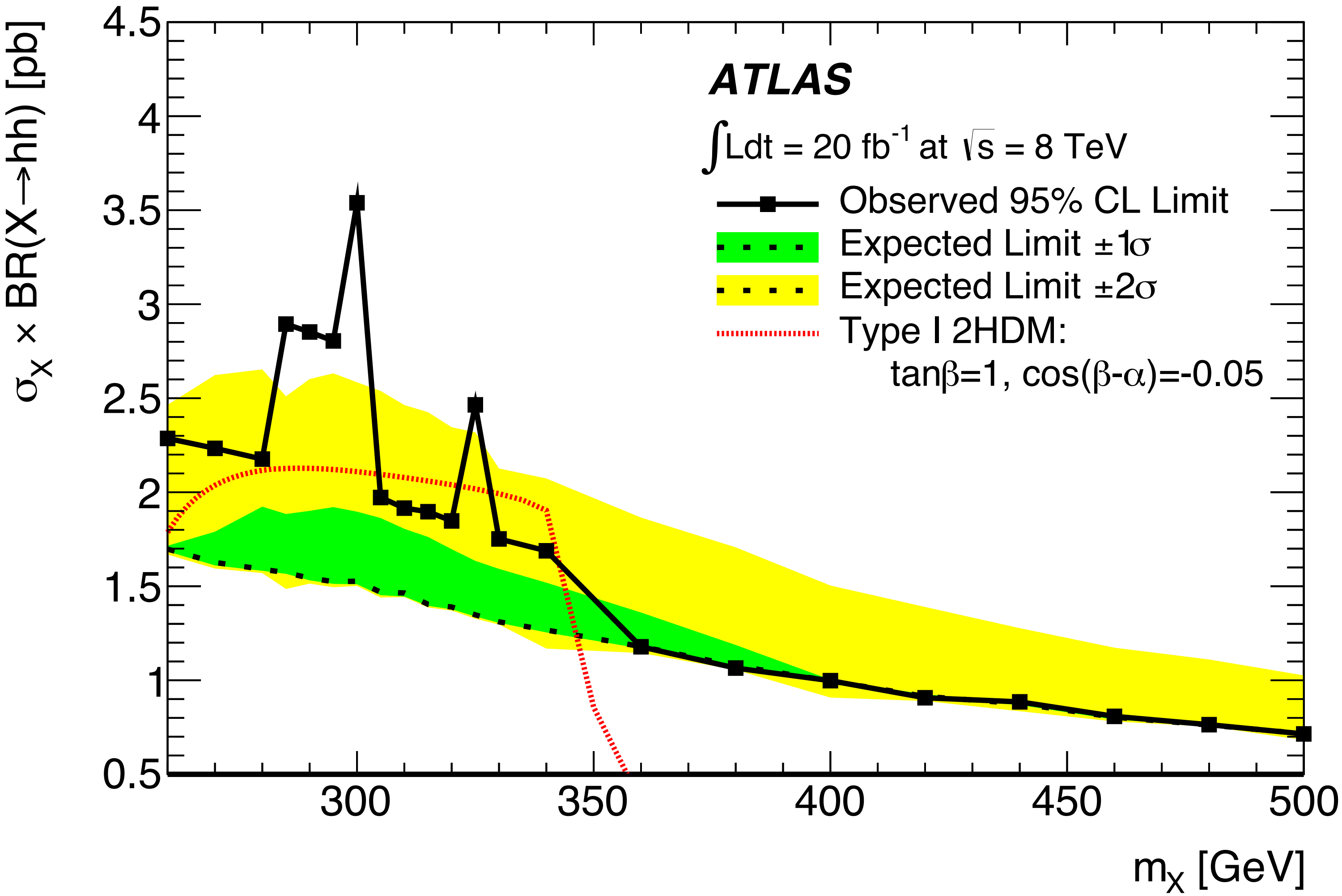
Systematic uncertainties in resonance search

All very small compared to statistical uncertainties

Systematic uncertainty		Resonance Analysis		
		SM $h+hh$ Bkgd	$H \to hh$ Signal	Continuum
Trigger	[%]	0.5		–
Luminosity	[%]	2.8		–
Photon	Identification [%]	2.4		–
	Isolation [%]	2		–
Mass	Resolution [%]	Migration: 1.6		–
	Position	Migration: 1.7%		–
Shape	$m_{\gamma\gamma}$ Continuum Shape [%]	–		11
	$m_{\gamma\gamma b\bar{b}}$: Statistical [%]	–		3-18
	$m_{\gamma\gamma b\bar{b}}$: jj vs bb [%]	–		0-30
	$m_{\gamma\gamma b\bar{b}}$: Fit Model [%]	–		16-30
Jets	b-Tagging [%]	3.4	2.4	–
	Energy Scale [%]	19	3.8	–
	b-jet Energy Scale [%]	6.5	2.2	–
	Energy Resolution [%]	15	9.3	–
Theory	PDF+Scale [%]	+18/-15	–	–
	Single h+HF [%]	14	–	–

Use simulation to evaluate differences in shape between γγbb and γγjj masses

Use alternate fit functions to Landau distribution


ATLAS
∫Ldt = 20 fb⁻¹ at √s = 8 TeV
Observed 95% CL Limit
Expected Limit ±1σ
Expected Limit ±2σ
Type I 2HDM:
tanβ=1, cos(β-α)=-0.05
σX × BR(X→hh) [pb]
mX [GeV]
4.5
4
3.5
3
2.5
2
1.5
1
0.5
300
350
400
450
500

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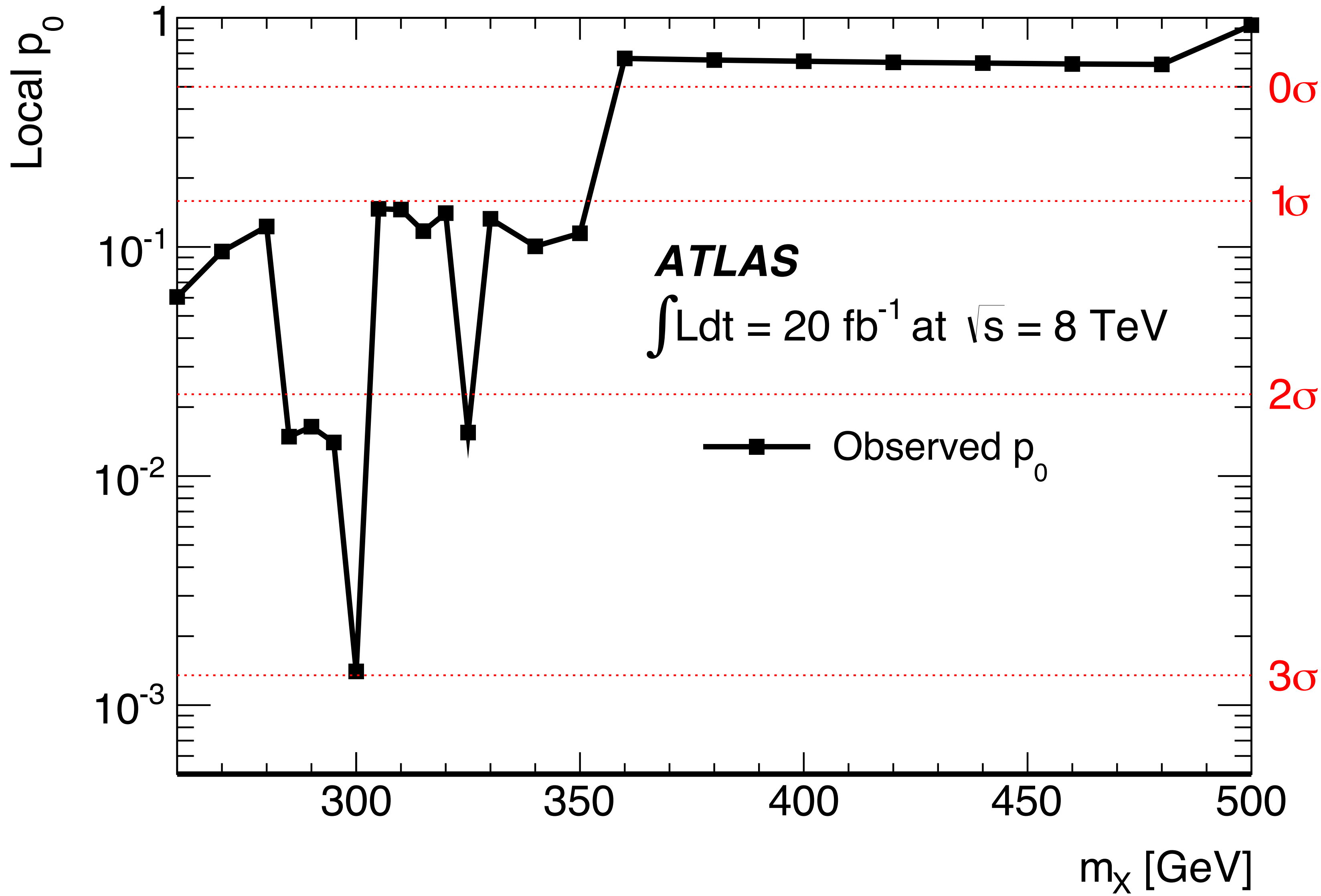
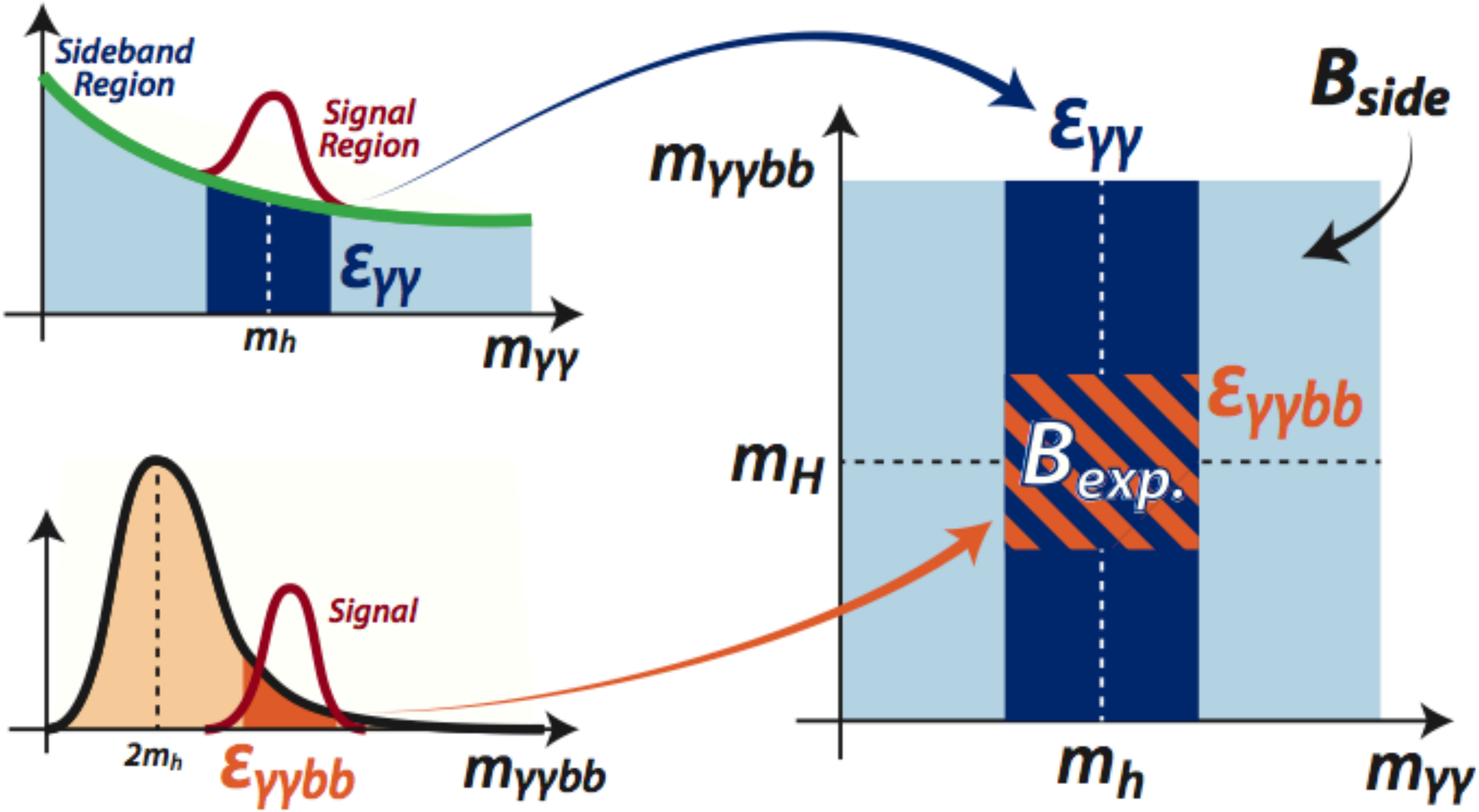


Global p-value = 2.1σ



Sideband Region
Signal Region
$\varepsilon_{\gamma\gamma}$
m_h
$m_{\gamma\gamma}$
Signal
$2m_h$
$\varepsilon_{\gamma\gamma bb}$
$m_{\gamma\gamma bb}$
$\varepsilon_{\gamma\gamma}$
B_{side}
$m_{\gamma\gamma bb}$
$\varepsilon_{\gamma\gamma bb}$
m_H
$B_{exp.}$
m_h
$m_{\gamma\gamma}$