Search for high mass scalar resonances in diboson decay modes at 13 TeV by the ATLAS collaboration

Ben Pearson on behalf of the ATLAS collaboration

2016 Phenomenology Symposium

The University of Oklahoma

Introduction

- Searches for an extension to the Higgs sector via an additional heavy, CP-even scalar singlet
- Using complete 2015 Dataset!
  - 3.2 fb^{-1} @ 13 TeV
- Many joint efforts between Higgs and Exotics groups yielding a variety of signal interpretations:
  - Scalar/Heavy-Higgs – spin 0
    - Widths from 4 MeV to 15% of m_X
    - Masses from 200 GeV to 3 TeV

    *Covered in this talk
  - Heavy Vector Triplet (HVT) – spin 1
  - Graviton – spin 2

    *See talk by Samuel Meehan

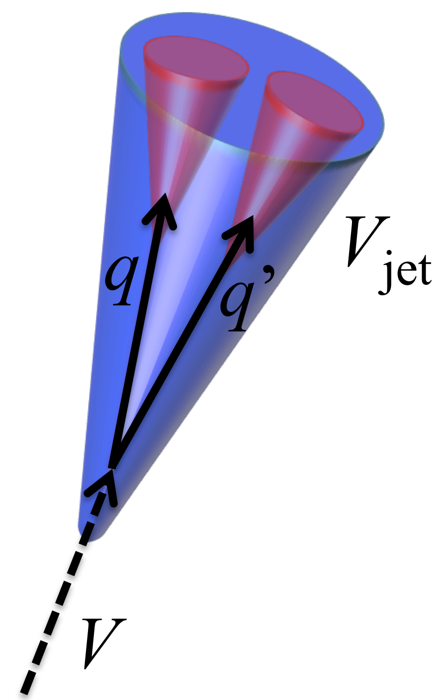
Outline

- This talk will highlight the most recent results:

		Documentation	Date
$X \to WW$	$lvqq + lvlv$ Combination	ATLAS-CONF-2016-021	April 2016
$X \to ZZ$	$llvv$	ATLAS-CONF-2016-012	March 2016
	$llqq$	ATLAS-CONF-2016-016	March 2016
	$vvqq$	ATLAS-CONF-2015-068	December 2015
$X \to VV$	$qqqq$	ATLAS-CONF-2015-073	December 2015
	Hadronic Combination	…	…coming soon
$X \to Z\gamma$	$ee\gamma + \mu\mu\gamma + qq\gamma$	ATLAS-CONF-2016-010	March 2016
$X \to \gamma\gamma$	-	ATLAS-CONF-2016-018	March 2016

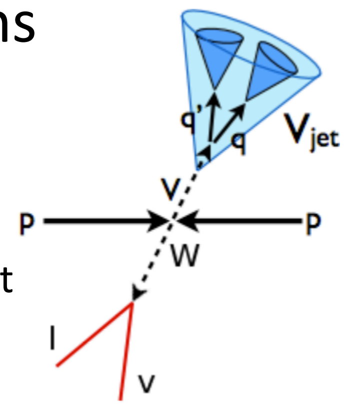
Some Tools and Methods

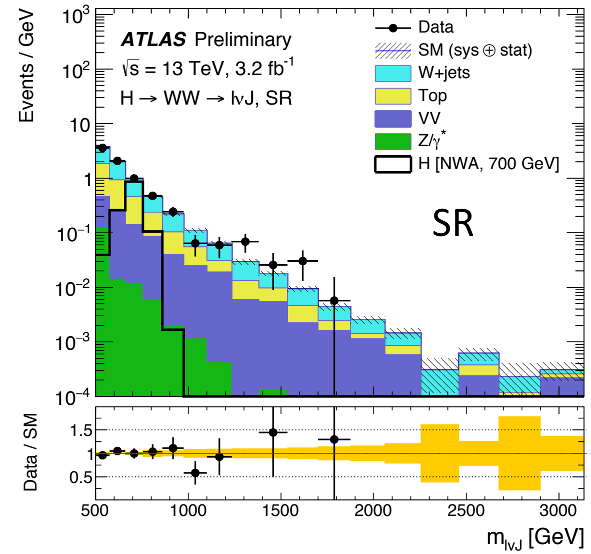
- Searches look for peaks in mass distributions
  - Smooth falling SM backgrounds
  - Searches with >1 neutrino use the transverse mass (m_T)
- High mass resonances result in highly boosted decay products
  - Collimated leptons and jets
  - Dedicated vector boson jet (V_{jet}) tagging
    - Both quarks are reconstructed in a single large-R jet
    - Tagger uses jet mass (m_J) and a substructure variable D_2: compatibility with a two-prong structure
    - m_J requirement to be within 15 GeV of m_W/m_Z
    - p_T dependent requirements on D_2 configured to give 50% signal identification efficiency

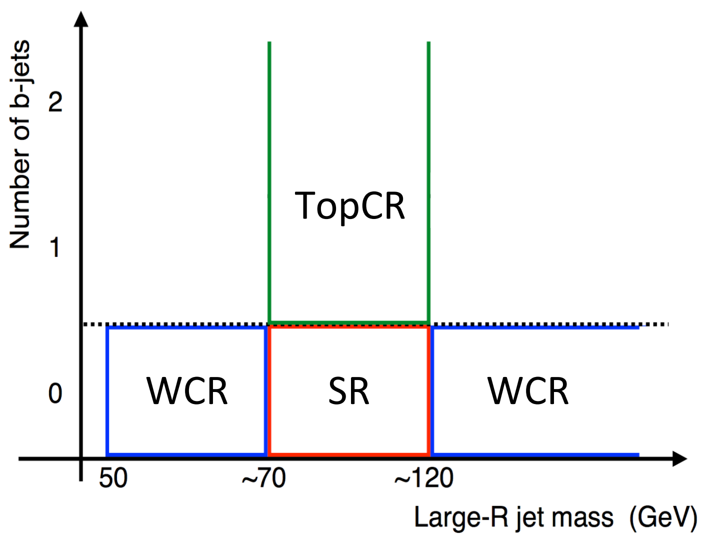


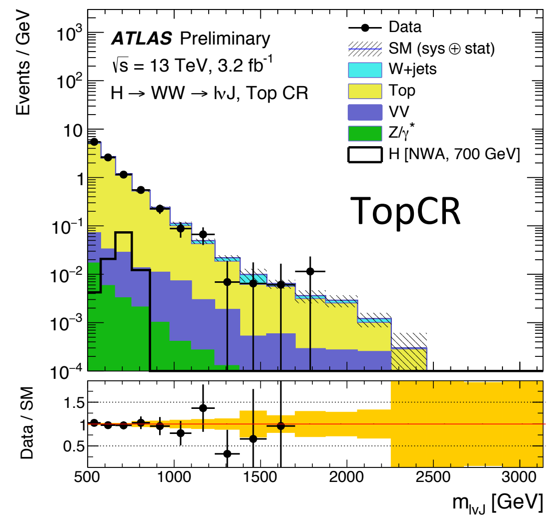
$X \rightarrow WW \rightarrow l\nu qq$

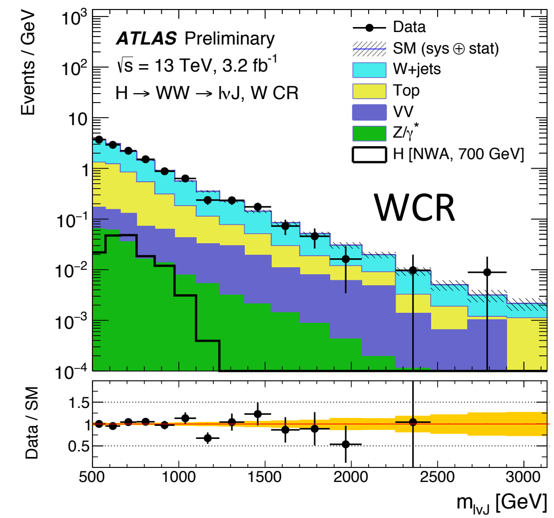
- Signals 500 GeV – 3000 GeV
  - Narrow, 5, 10, and 15% widths
- Dominant backgrounds
  - Top ($t\bar{t}$) and *W*+jets
    - Normalized using CRs in simultaneous fit
- Fit discriminant $m_{l\nu J}$
  - Using: m(*lv*) = m(*W*)





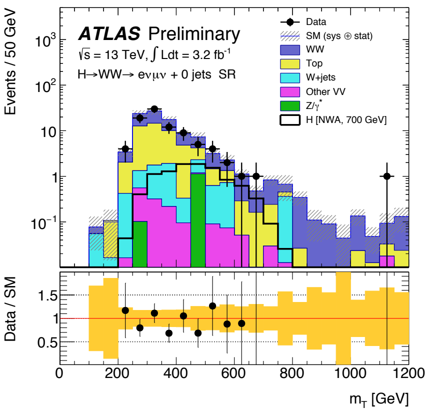


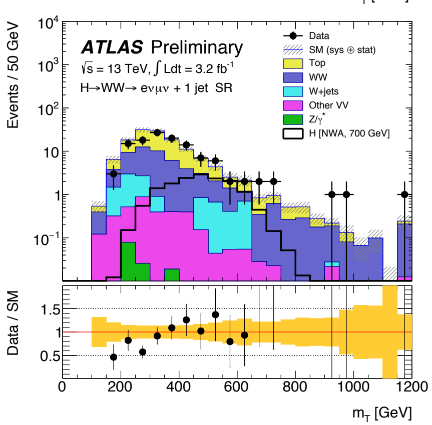


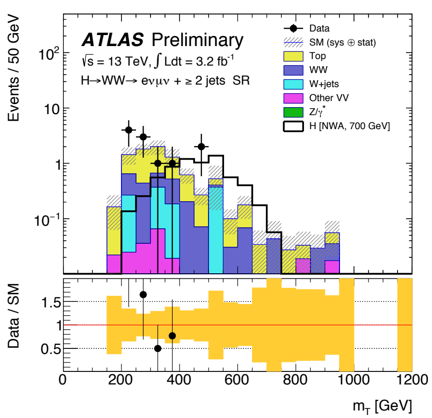


$X \rightarrow WW \rightarrow l\nu l\nu$

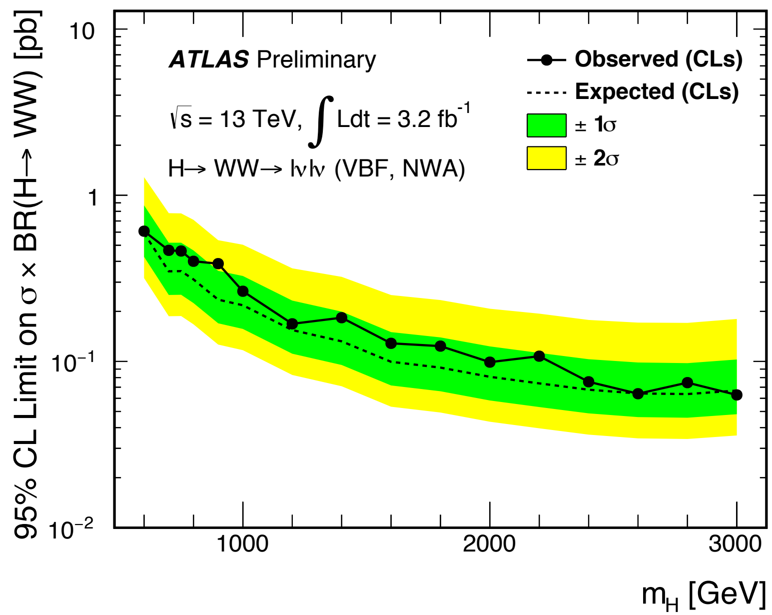
- Similar approach to semi-leptonic channel
  - Dominant bkgs.: top-quark and *WW* productions → use control regions
  - Fit discriminant transverse mass: $m_T = \sqrt{\left(\sqrt{|\mathbf{p}_T^{ll}|^2 + m_{ll}^2} + E_T^{miss}\right)^2 - |\mathbf{p}_T^{ll} + \boldsymbol{E}_T^{miss}|^2}$
- SR split by N_{jet} (0, 1, ≥2) advantage of different bkg. comp.





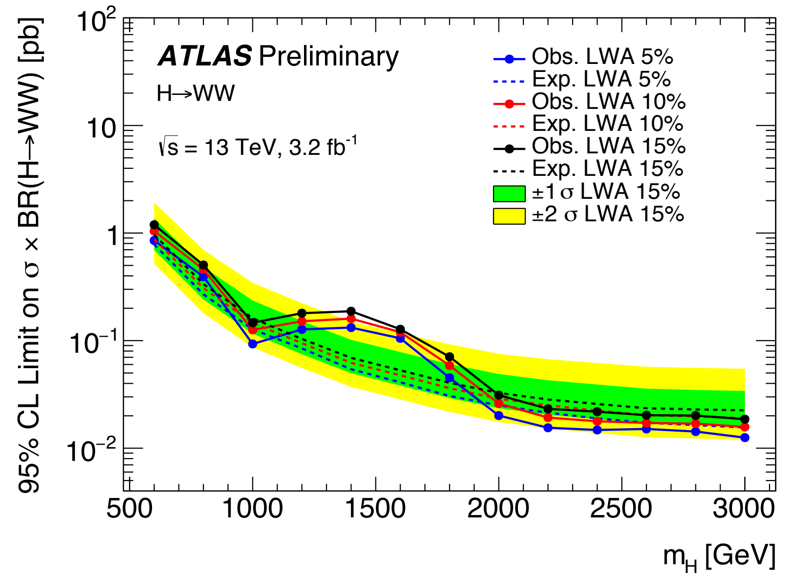


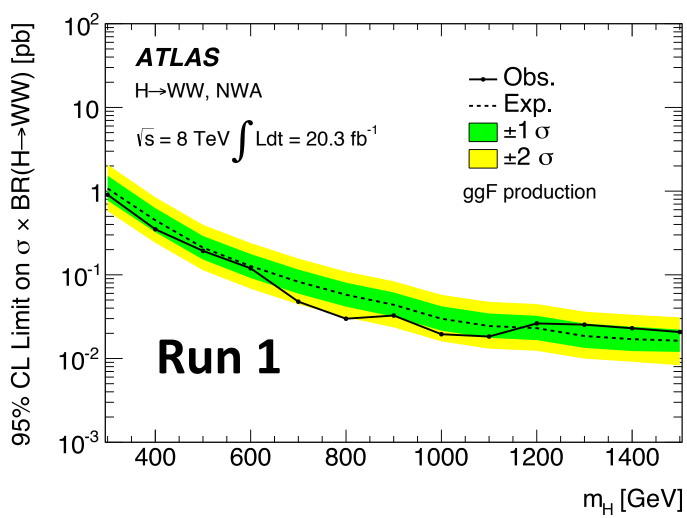
- Limits also set on VBF production σ x BR
  - For NWA
  - Expect. limit $\sigma_{ggF} = 0$
  - Obs. limit σ_{ggF} is nuisance parameter

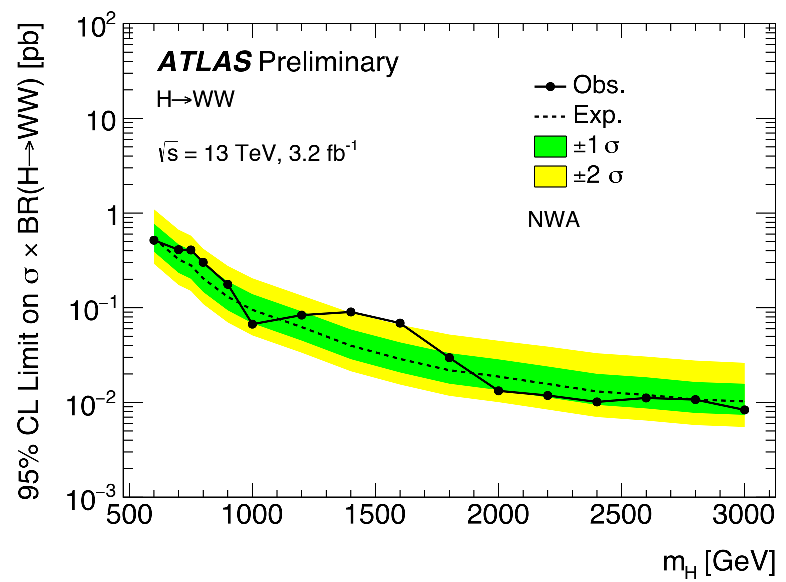


$X \rightarrow WW$ Combined

- ggF combination (*lvlv* N_{jet}=0,1)
- Maximum-likelihood fit (SR and CRs)
- No excess → set limits σ x BR
- *lvqq* dominates in entire mass range
- Significantly expanded the mass range from Run 1 (8 TeV data)
  - JHEP01(2016)032

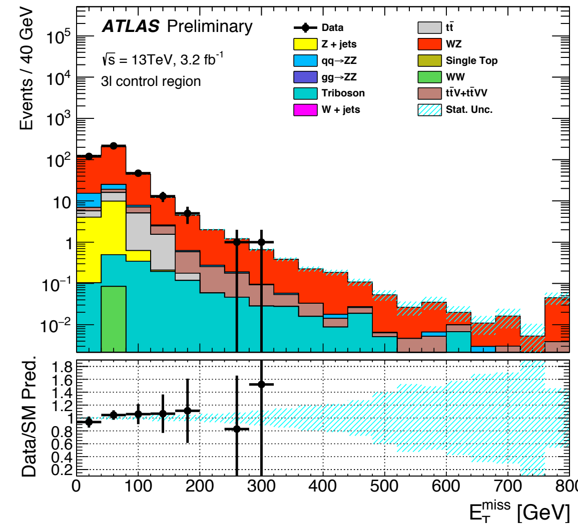




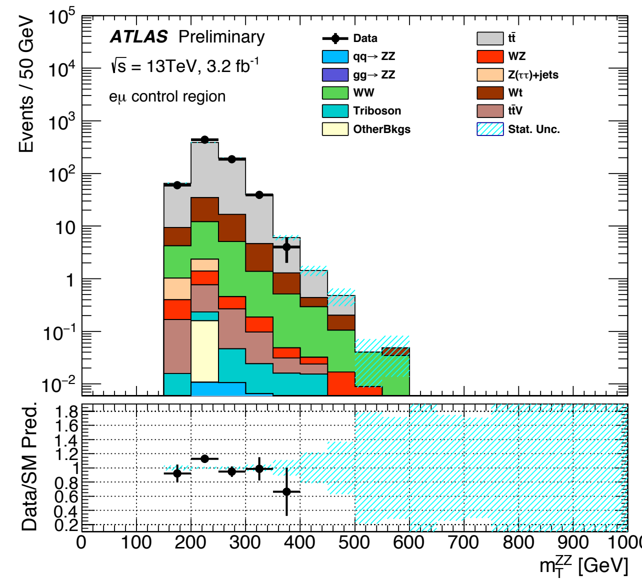


X→ZZ→llνν

- Important backgrounds
  - *ZZ*, *WZ*, *Z*+jets, and less so *WW*, *tt*, *Wt*, and *Z*→*ττ*
- 3-lepton CR for *WZ* normalization
- *eμ* CR for inclusive estimate of WW, tt, Wt, and Z→ττ processes
- Discriminant: $m_{\mathrm{T}}^{ZZ} = \sqrt{\left(\sqrt{m_Z^2 + |\mathbf{p}_{\mathrm{T}}^{ll}|^2} + \sqrt{m_Z^2 + |E_{\mathrm{T}}^{\mathrm{miss}}|^2}\right)^2 - |\mathbf{p}_{\mathrm{T}}^{ll} + \boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}|^2}$

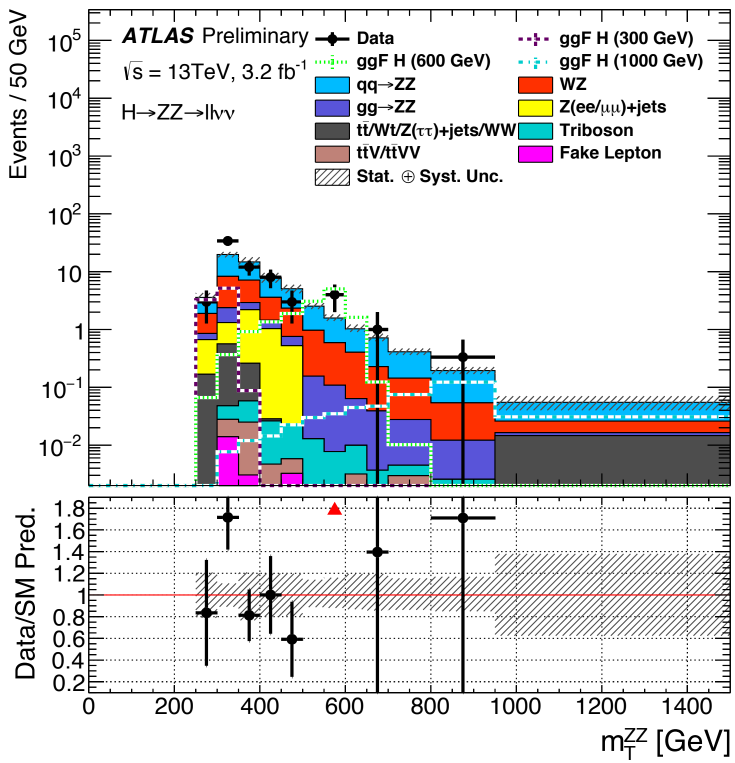


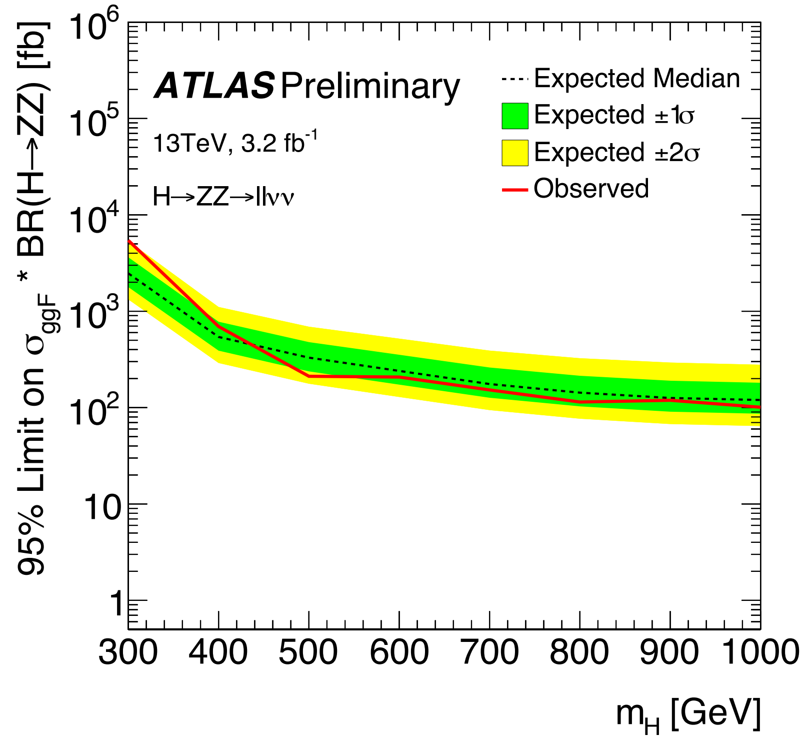
Variables	Cut Values
Lepton p_{T} (leading, subleading)	>(30 GeV, 20 GeV)
$m_{\ell\ell}$	76–106 GeV
$E_{\mathrm{T}}^{\mathrm{miss}}$	>120 GeV
$\Delta R_{\ell\ell}$	<1.8
$\Delta\phi(\vec{p}_{\mathrm{T}}^{\ell\ell}, \vec{E}_{\mathrm{T}}^{\mathrm{miss}})$	>2.7
Fractional p_{T} difference	<0.2
Number of b-jets	0
$\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \mathrm{jets})$	> 0.4
$p_{\mathrm{T}}^{\ell\ell}/m_{\mathrm{T}}^{ZZ}$	< 0.7



$X \rightarrow ZZ \rightarrow ll\nu\nu$

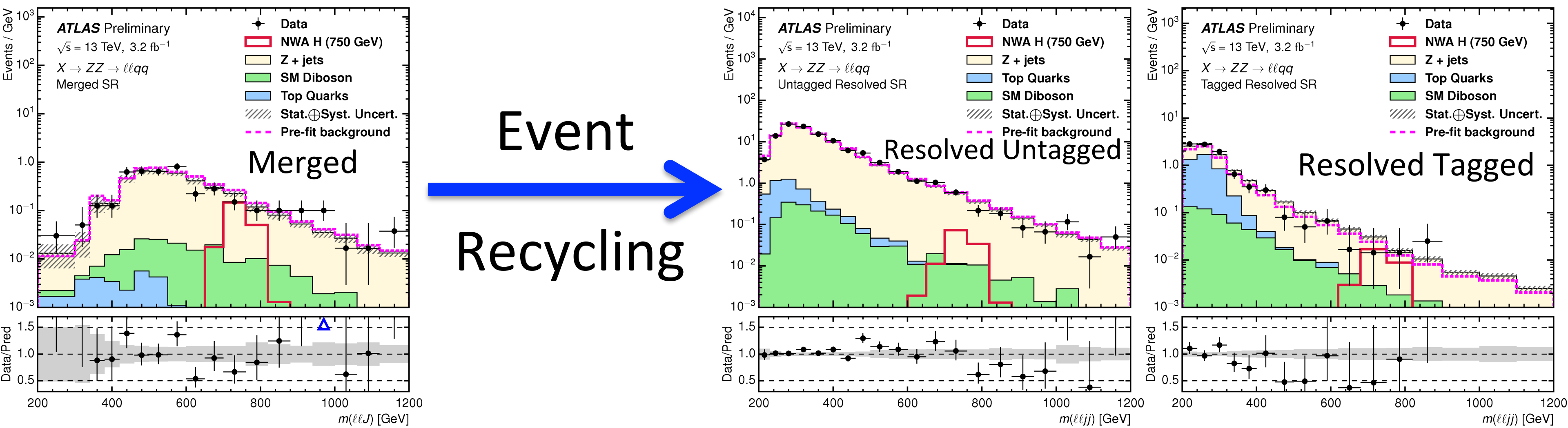
- The number of data points and the m_T^{ZZ} distributions are consistent with the SM predictions
- Upper limits are set on the σ x BR for NWA
  - For each mass point (300-1000 GeV)





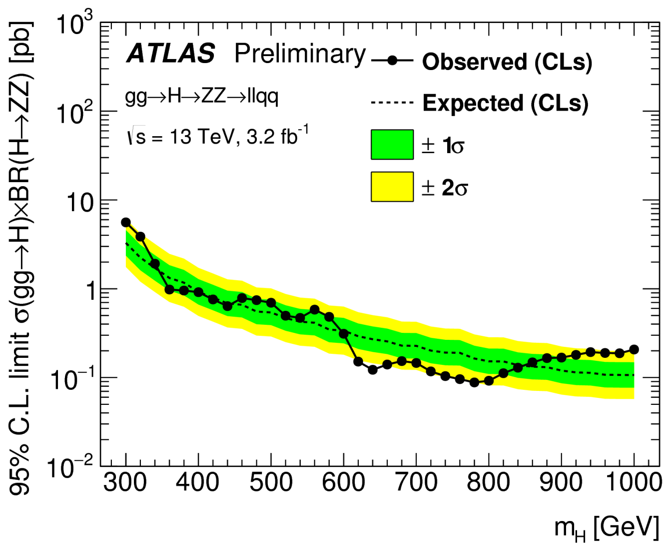
$X \to ZZ \to llqq$

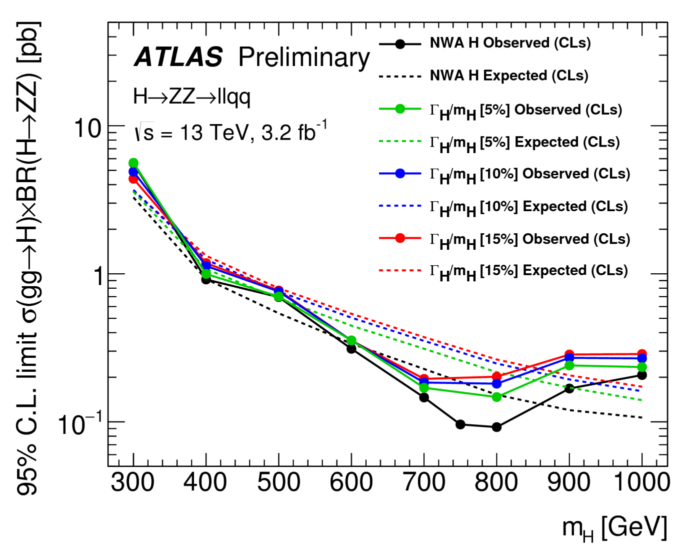
- Merged **and** resolved reconstruction of the $Z \to qq$ decay
  - **Merged**: one *Z*-tagged large-*R* jet (J) and **resolved**: a pair of small-*R* jets (jj)
- Events failing merged analysis selection are "**recycled**" to resolved
- Resolved analysis further categorization
  - b-tagged jets: exactly 2 (tagged) and < 2 (untagged)
- **Dominant bkgs.**: *Z*+jets, diboson, top
- **Control regions**: Top CR for resolved tagged region (diff. flavor l's & $m_{bb} \approx m_{top}$)
  Z+jets CR for each signal region ($m_{J/jj}$ side-bands)



$X \to ZZ \to llqq$

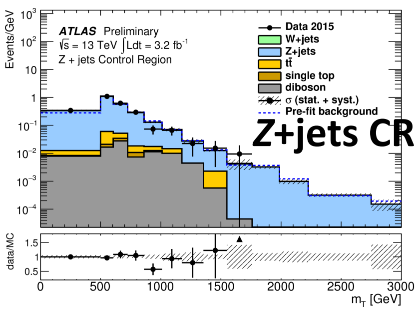
- The three signal regions and four CRs are fit simultaneously
  - Constraining the normalization of the *Z*+jets and Top backgrounds
  - Discriminant is the full invariant mass m_{llJ} / m_{lljj}
- No significant excess is observed
- Upper limits are set on the σ x BR for NWA and LWA
  - For each mass point (300-1000 GeV) and width (NWA & 5,10,15%)

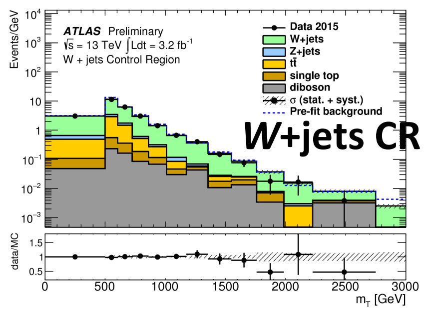


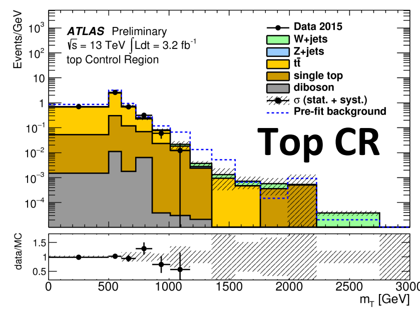


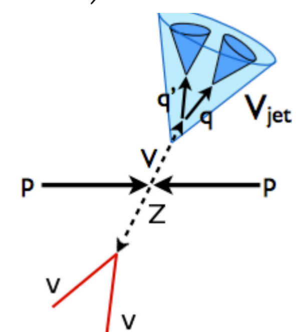
X→ZZ→ννqq

- Dominant bkgs: *Z*+jets, *W*+jets, and ttbar
  - Normalized using dedicated control regions in a combined fit
- Fit discriminant transverse mass: $m_{\mathrm{T}} = \sqrt{\left(\sqrt{m_J^2 + |\mathbf{p}_{\mathrm{T}}^J|^2} + E_{\mathrm{T}}^{\mathrm{miss}}\right)^2 - |\mathbf{p}_{\mathrm{T}}^J + \boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}|^2}$

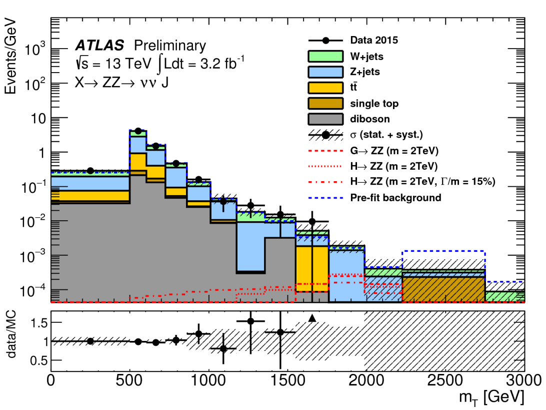


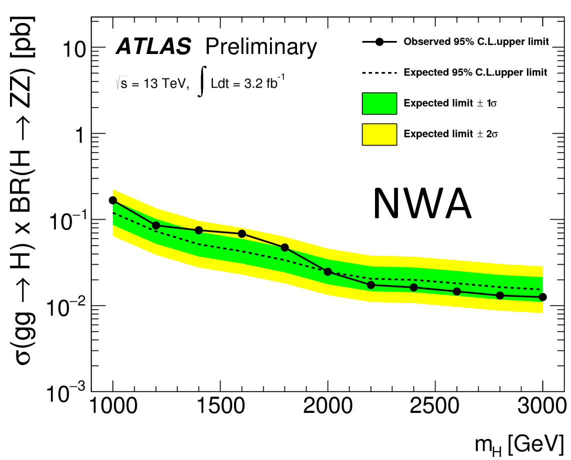


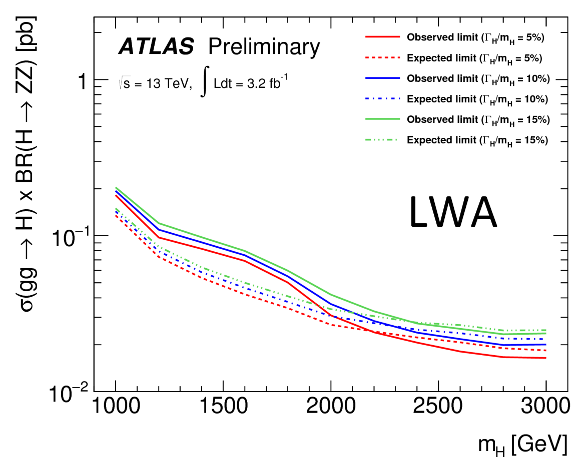




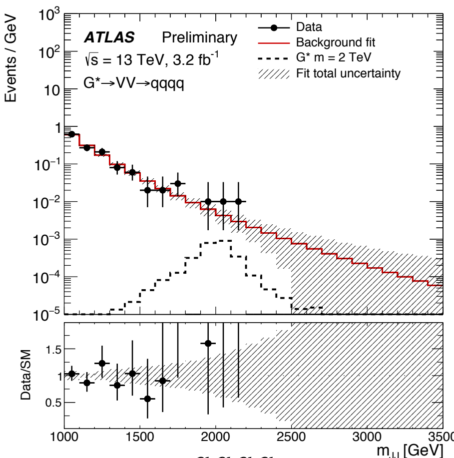
- Signal region: lepton veto, MET>250 GeV, Z-tagged large-*R* jet, 0 b-jets



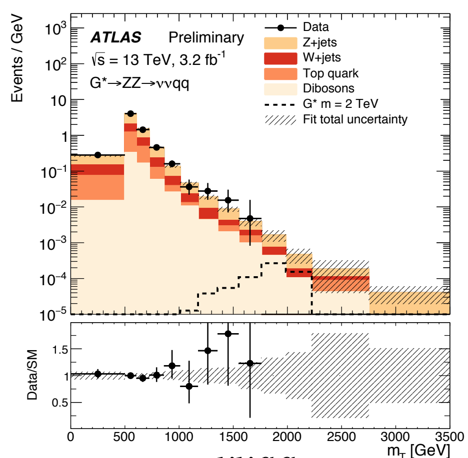




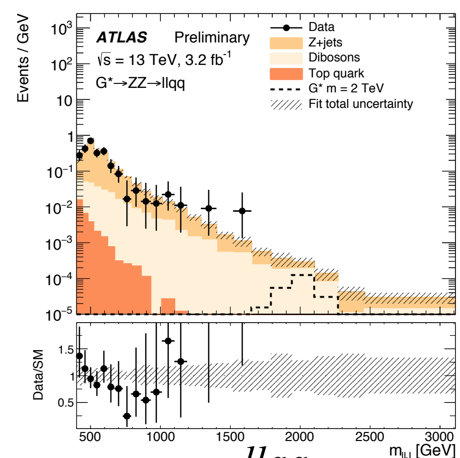
$X \rightarrow VV$ Hadronic Combination



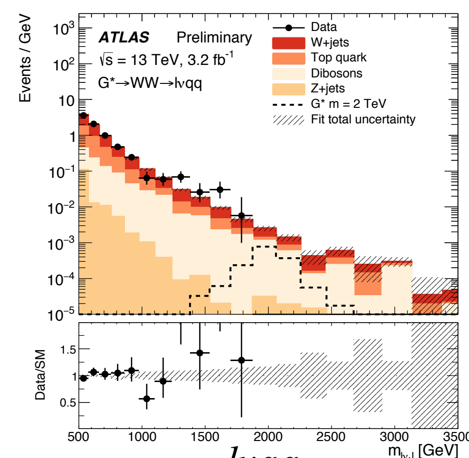
qqqq



ννqq

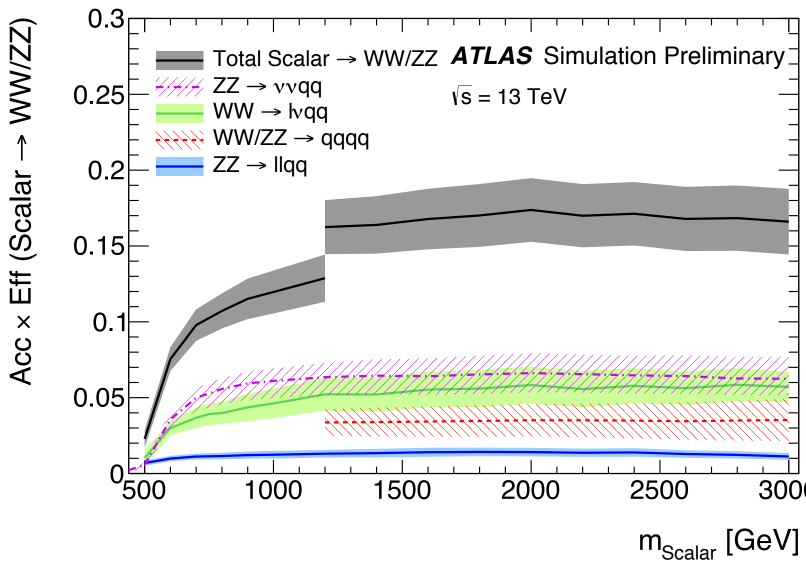


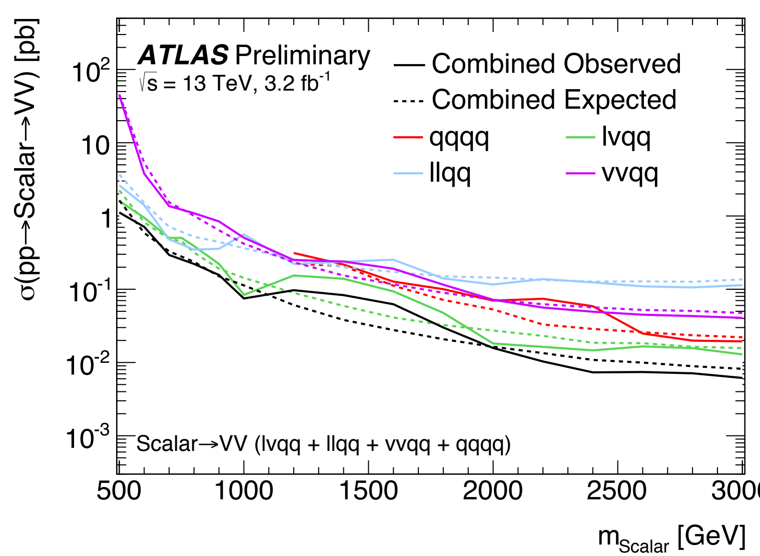
llqq



lνqq

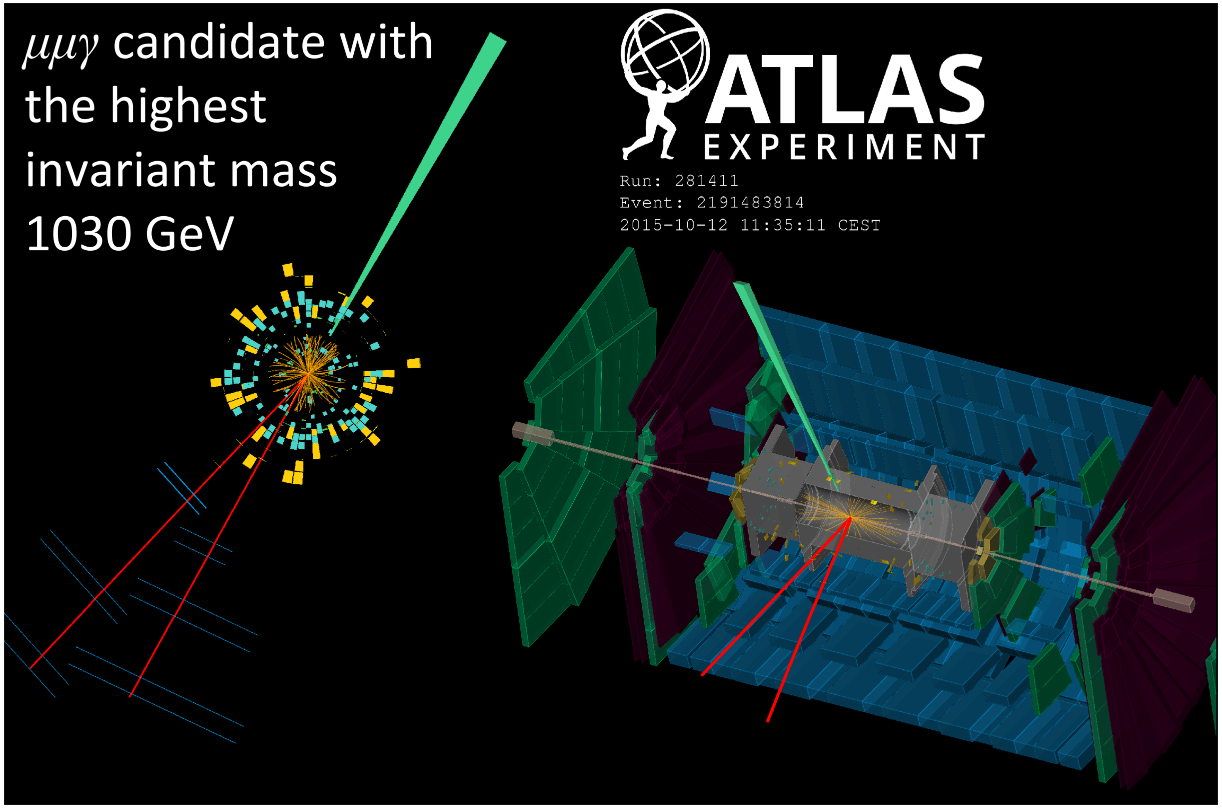
- Although G* signal is shown above, results below use scalar signal
- No significant excess observed, so combined limits set on σ x BR





$X \to Z\gamma$, $Z \to ee, \mu\mu, qq$

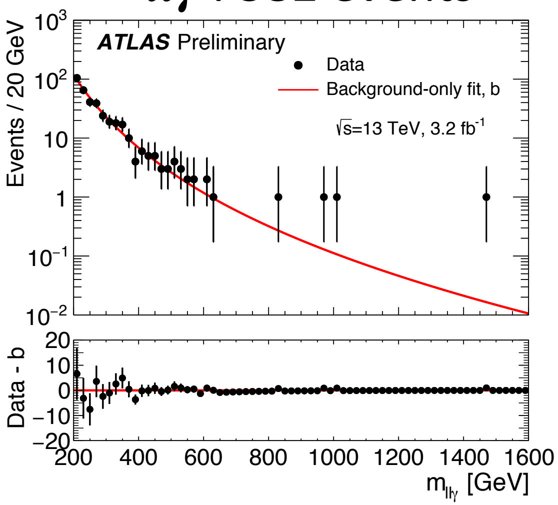
- Search for localized excess in the invariant mass distribution
- Leptonic ($ll\gamma$) and hadronic ($J\gamma$) analyses
  - $l = e,\mu$ and J = large-*R* jet
- **Dominant Bkgs.**
  - Leptonic
    - Z+γ continuum
  - Hadronic
    - γ+**jet** non-resonant SM production
- Discriminant
  - Invariant mass $m_{ll\gamma}/m_{J\gamma}$



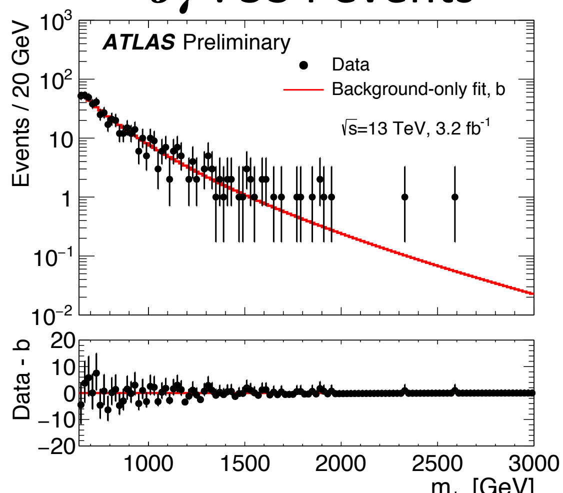
$X \to Z\gamma$, $Z \to ee, \mu\mu, qq$

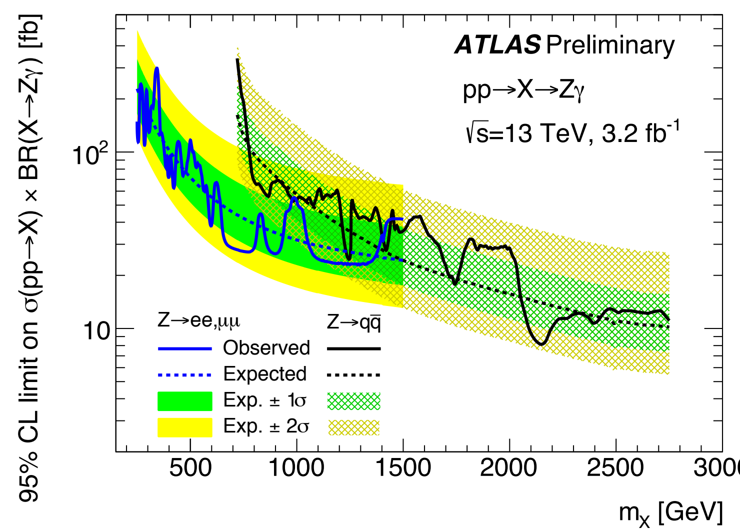
- Signals Γ_X = 4 MeV (m_X = 200-3000 GeV)
  - **Leptonic Sel**: $p_T(\gamma) > 0.3 m_{ll\gamma}$, and $m_{ll} = m_Z \pm 15$ GeV
  - **Hadronic Sel**: $p_T(\gamma)$ > 250 GeV, *Z*-tagged $p_T(J)$ > 200 GeV
- Total background exhibits smoothly falling mass spectrum
  - Parameterized by smooth function with data-adjusted parameters
- Maximum-likelihood fit to $m_{ll\gamma}/m_{J\gamma}$ → limits on the σ x BR

llγ : 382 events



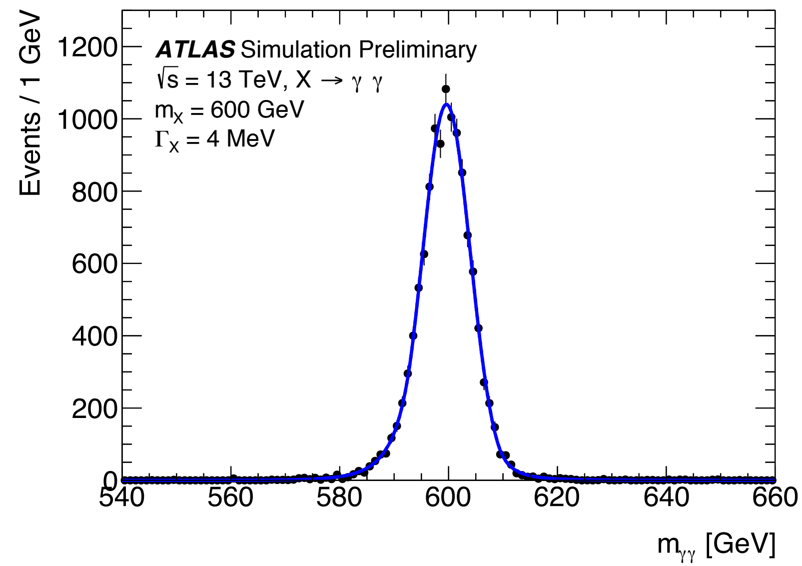
Jγ : 534 events

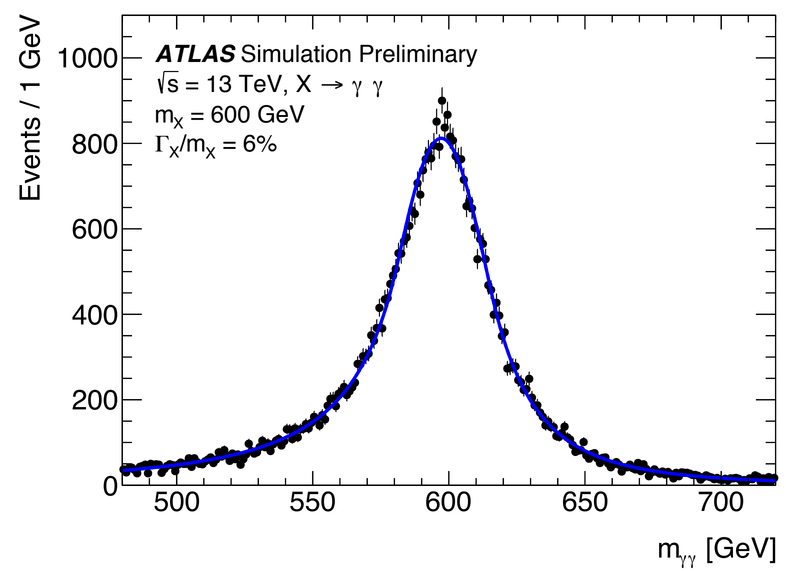




$X \rightarrow \gamma\gamma$

- **Signals** m_X = 200 – 2000 GeV
  - Widths (Γ_X) up to Γ_X/m_X = 10%
    - Including a narrow width: 4 MeV
    - Large width generation for $m_X \pm 2\Gamma_X$
      - Reduce model effects from off-shell region
  - $m_{\gamma\gamma}$ experimental resolution modelled by a DSCB function
- **Selection**:
  - Diphoton trigger: E_T > 35(25) GeV
    - leading (sub-leading) photon
  - 2 identified and isolated photons
    - With E_T > 40(30) GeV
  - $E_T/m_{\gamma\gamma}$ > 0.4(0.3)

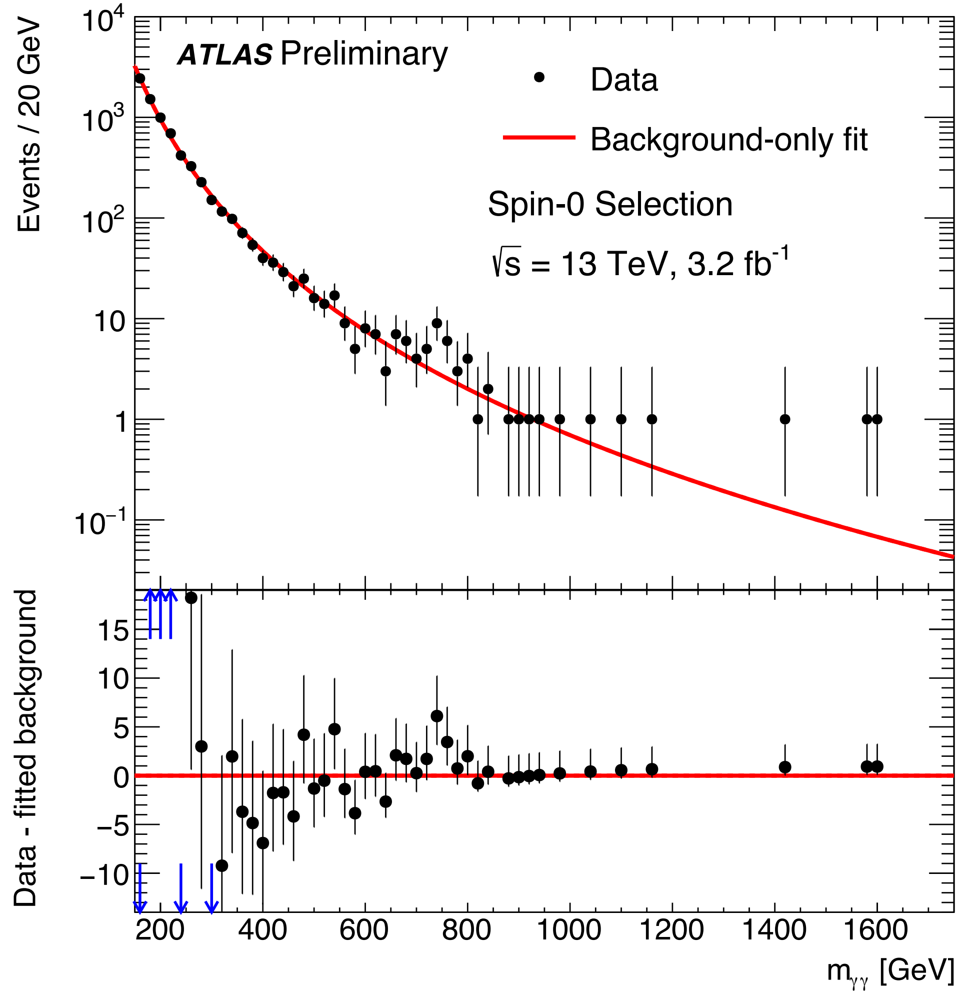




$X \rightarrow \gamma\gamma$

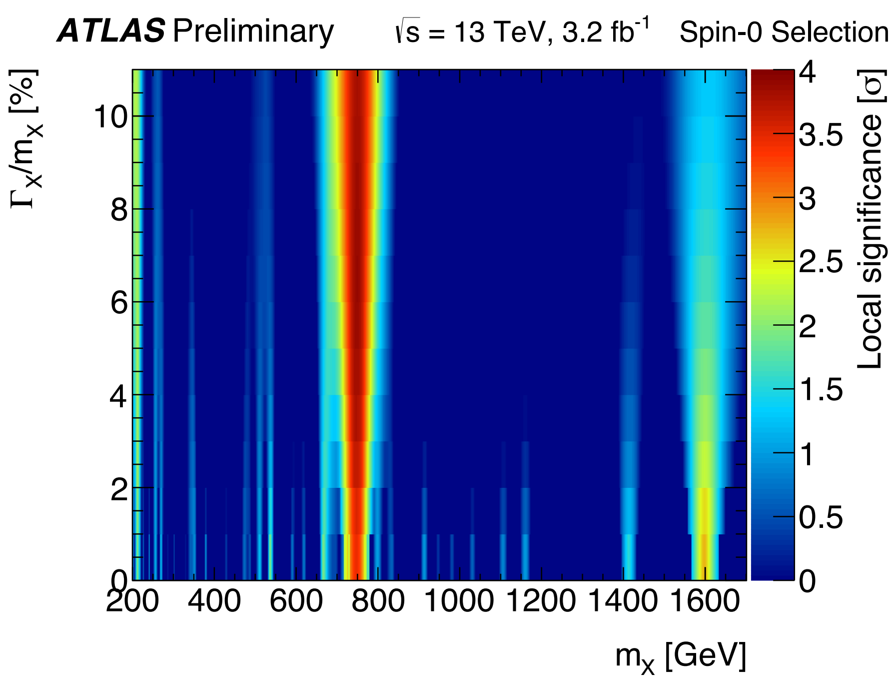
- **Background estimation**
  - $\gamma\gamma$ QCD from MC
  - γ+jet and dijet from CRs
  - $m_{\gamma\gamma}$ distribution shape
    - Functional form: $f = (1 - x^{1/3})^b x^a$
      - b and a determined by data
      - $x = m_{\gamma\gamma}/\sqrt{s}$
- **Maximum-likelihood fits**
  - Entire mass spectrum is used for each mass hypothesis
  - B-only to S+B likelihood ratios for local significances

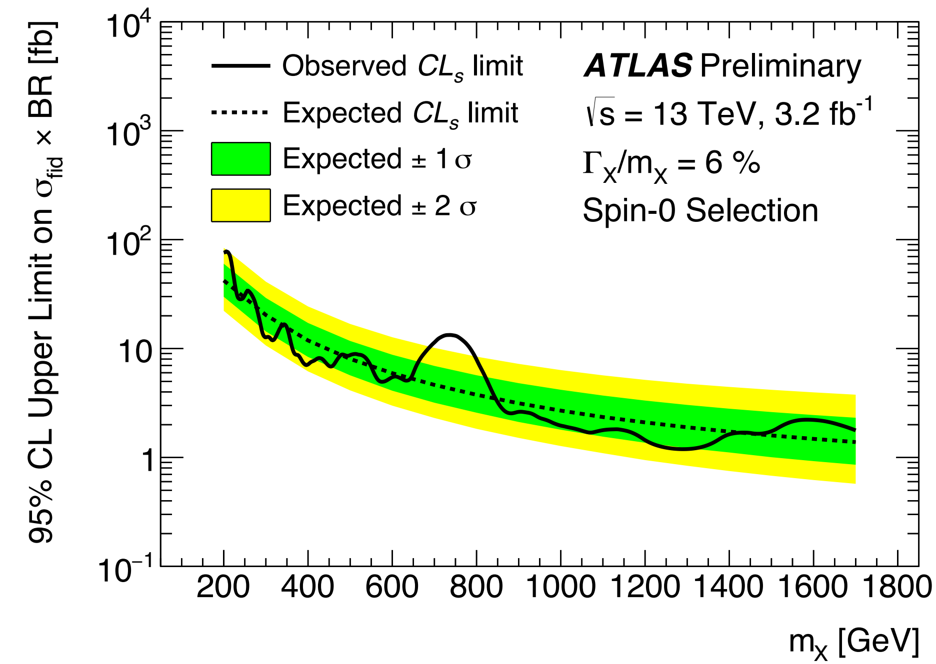
2878 events ($m_{\gamma\gamma}$ > 200 GeV)



$X \rightarrow \gamma\gamma$

- Largest deviation observed around m_X = 750 GeV
  - 3.9σ (2σ global) with a Γ = 45 GeV (6%) signal width
    - Global significance accounts for look-elsewhere-effect using pseudo-experiments
- Not enough for discovery, so limits on σ_{fid} evaluated
  - Fiducial cross-section to minimize model dependence





Summary and Outlook

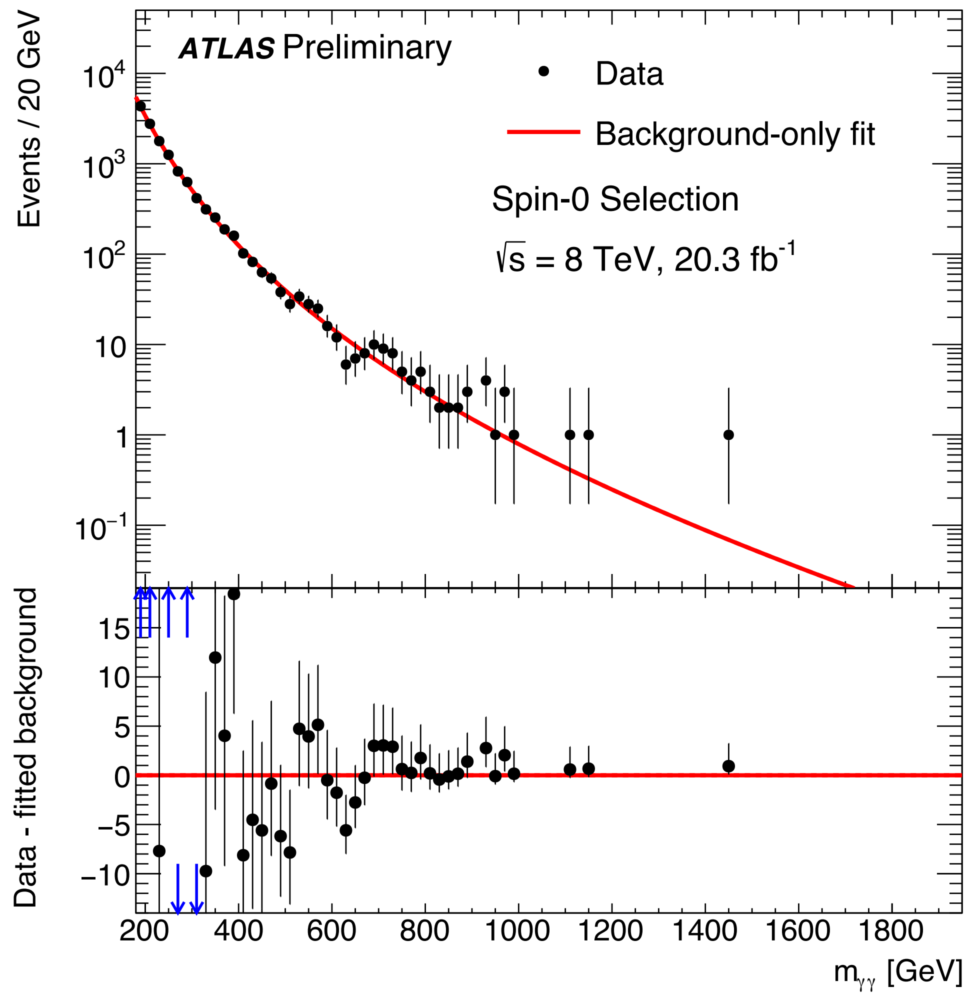
- Just the tip of the iceberg!?
- Eager for **more data!**
  - May have 6-8 fb^{-1} by ICHEP and >20 fb^{-1} by the end of the year
- Collaboration is working hard to output results as efficiently as possible

- Always room for improvement
  - Large-*R* jet systematics dominate most hadronic channels
  - Improvements to large-*R* jet mass resolution in progress
- The future is bright! Bring on the lumi!

Backup Material

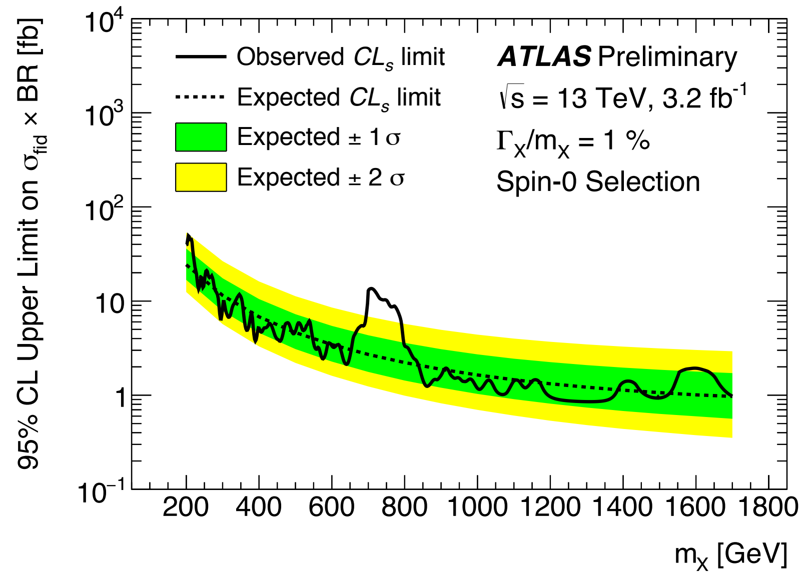
$X \to \gamma\gamma$

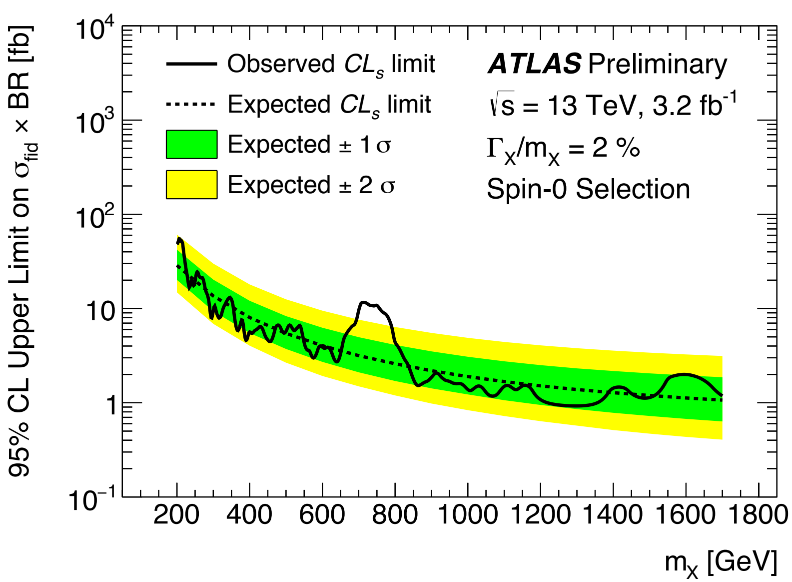
- **Comparison with 8 TeV data**
- 20 fb^{-1} reanalyzed data
  - Newest 8 TeV photon energy calibration
  - Same ID and isolation
  - Extended mass range
- 750 GeV and 6% = Γ/m_X signal hypothesis
  - Excess of 1.9σ @ 750 GeV
  - Difference between 8 and 13 TeV results corresponds to a statistical significance of 1.2σ (2.1σ) for gg(qq) production

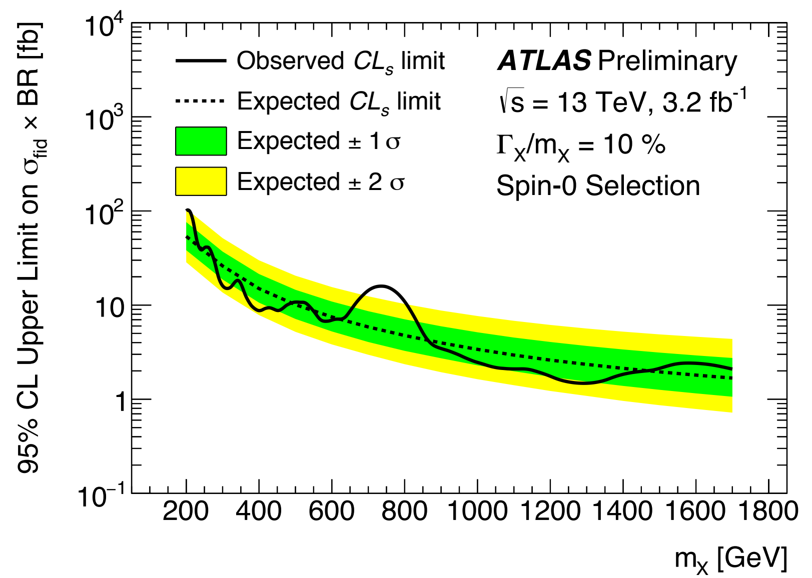


$X \rightarrow \gamma\gamma$

- Limits for other widths:

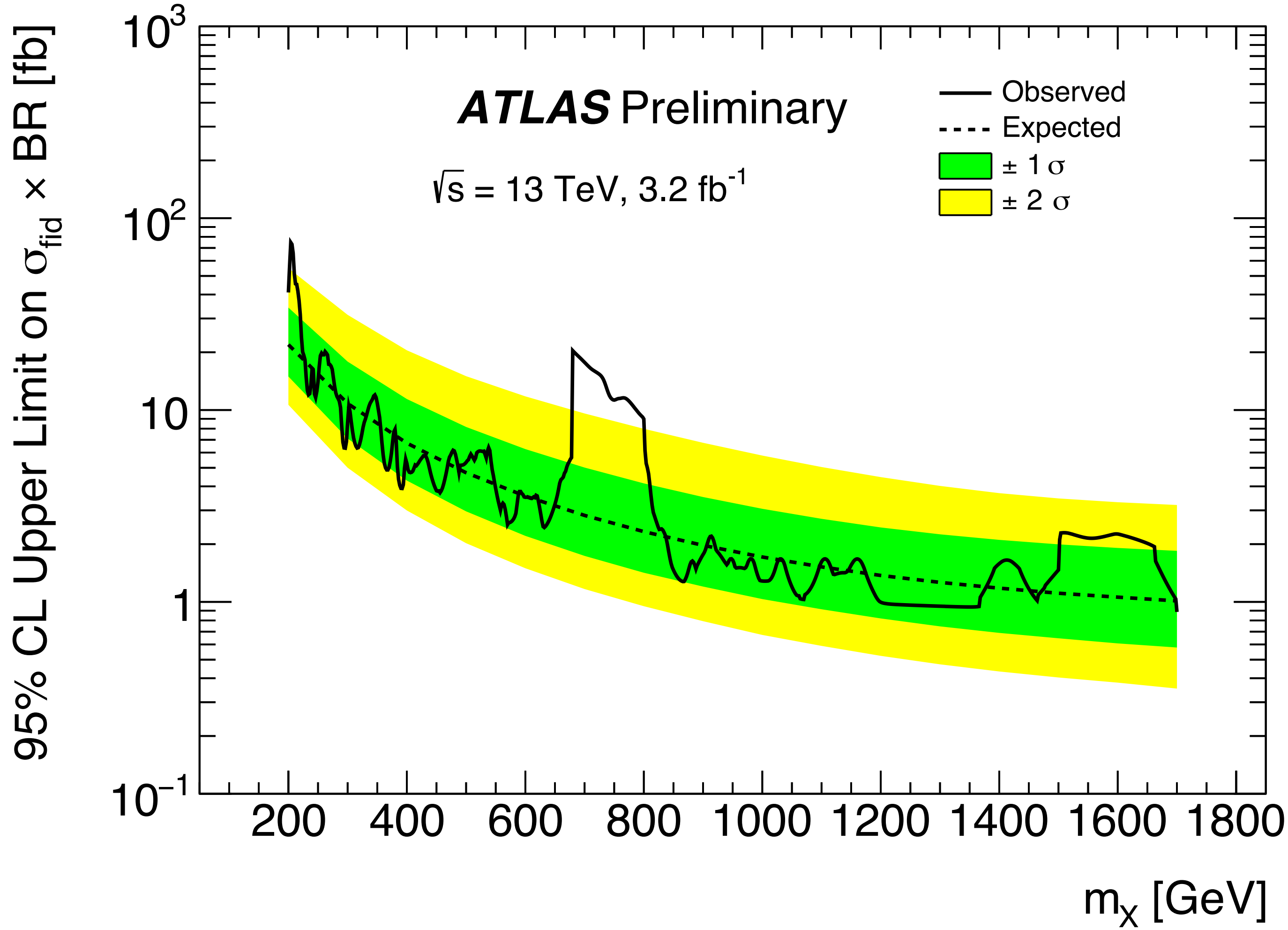






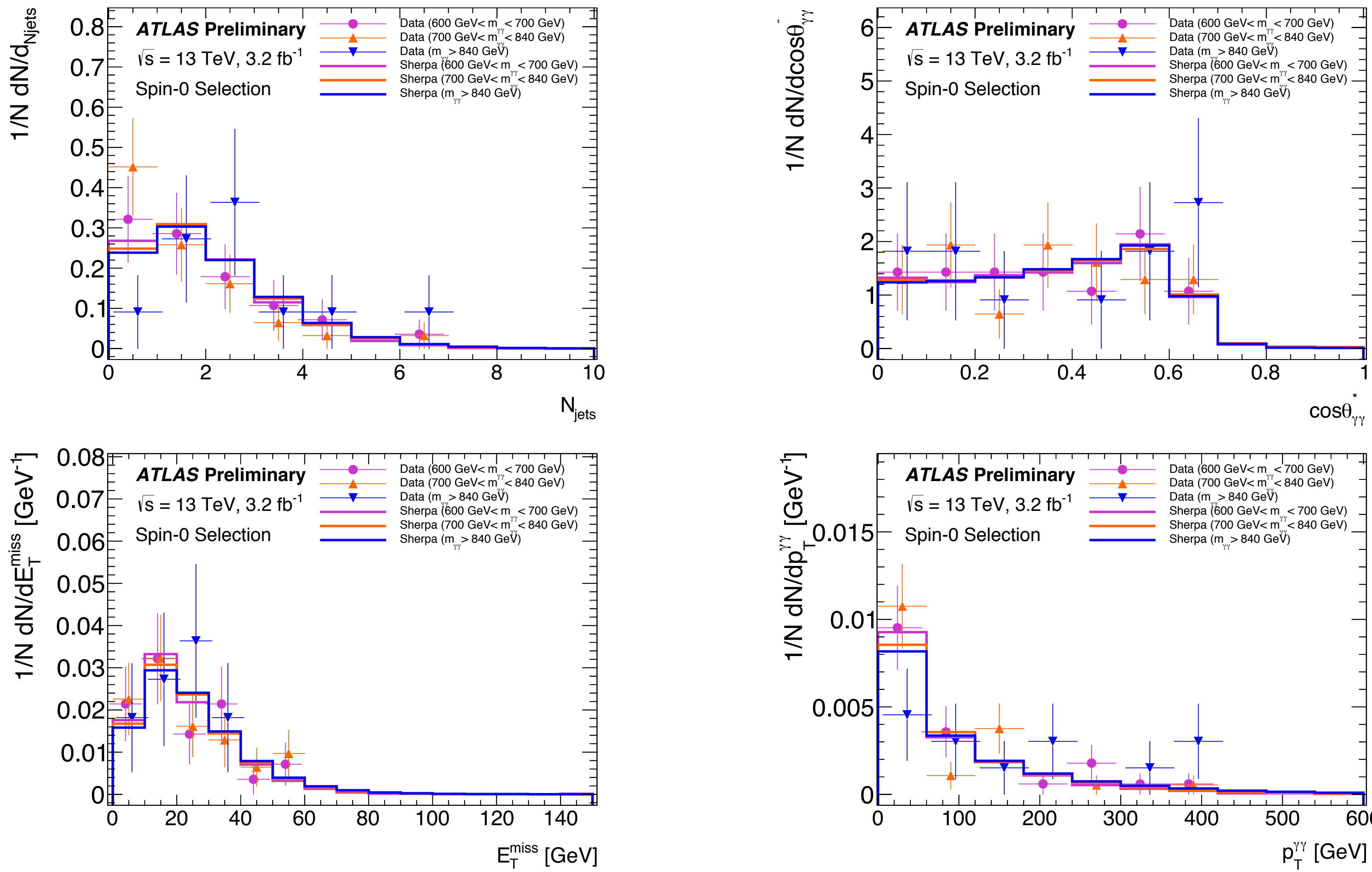
$X \rightarrow \gamma\gamma$

- Limit for a narrow width 4 MeV signal (previous CONF note)



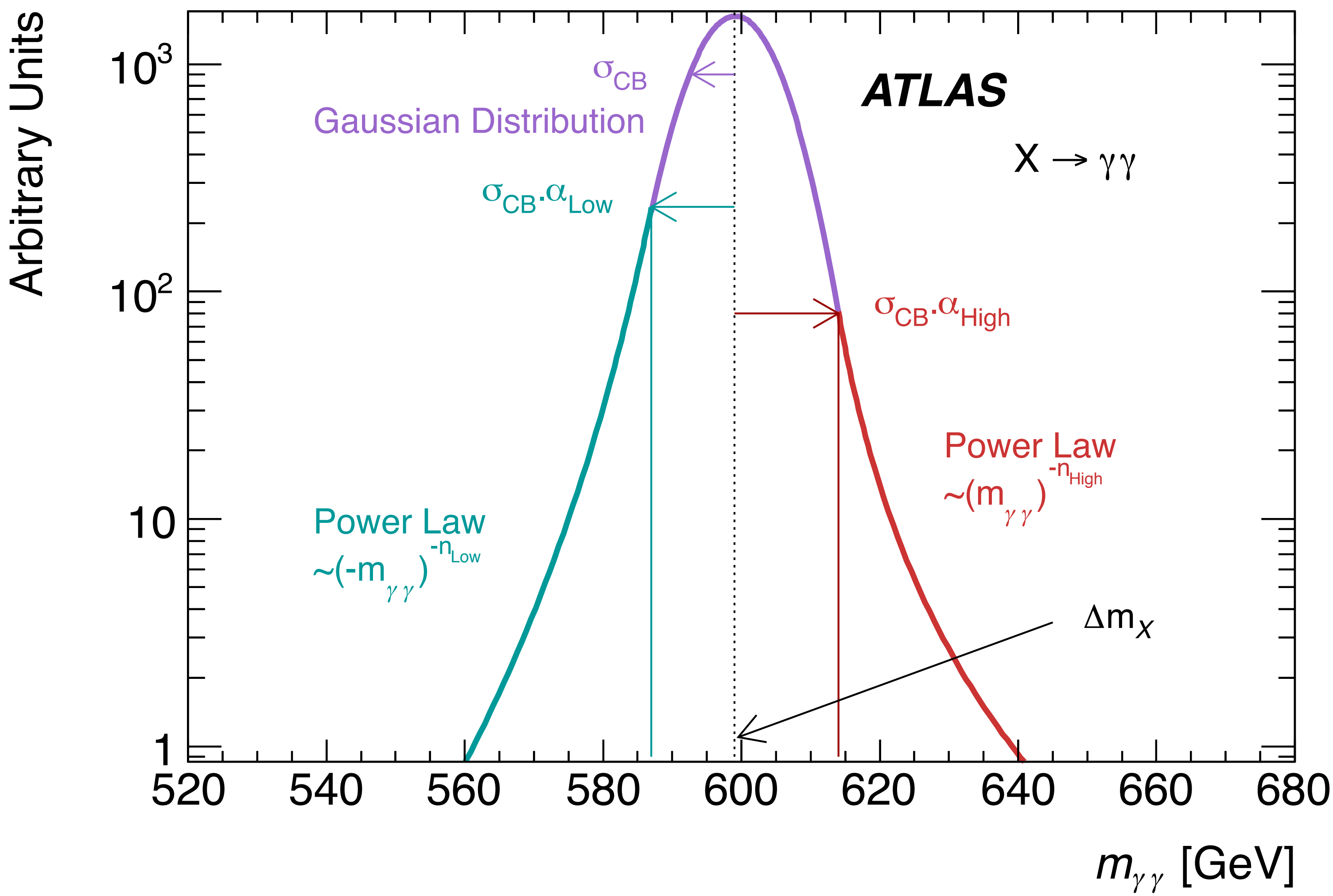
$X \to \gamma\gamma$

- Kinematic distribution sanity checks:



$X \to \gamma\gamma$

- Double-sided Crystal Ball function:



$X \rightarrow ZZ \rightarrow llqq$

- **Control regions**:
  - Top CR for resolved tagged region (diff. flavor l's & $m_{bb} \approx m_{top}$)
  - Z+jets CR for each signal region ($m_{J/jj}$ side-bands)