Searches for diboson resonances with the ATLAS detector at the LHC

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Introduction

Diboson searches in this talk:

- $VV \to qqqq$ [1] (V: W or Z boson)
- $VV \to \nu\nu qq$ [2], $\ell\nu qq$ [3], $\ell\ell qq$ [4]
- $VH \to \nu\nu bb$, $\ell\nu bb$, $\ell\ell bb$ [5]
- $\gamma\gamma$ [6] and $Z\gamma$ [7]

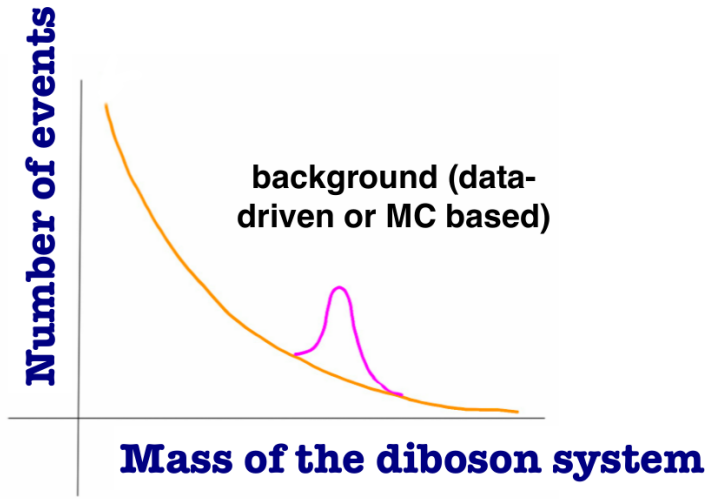
Based on $\sqrt{s} = 13\,\text{TeV}$, $3.2\,\text{fb}^{-1}$ data

Benchmark models:

- Spin 0: extended Higgs-sector
- Spin 1: Heavy Vector Triplets (HVT) $\to W', Z'$
- Spin 2: Randall-Sundrum Graviton (RSG)

Search strategy:

- Reconstruct decay products of resonance X
- Expect peak in m_X spectrum
- Continuous background from SM processes



Run 1 results in diboson searches

Run 1 excess in W' searches

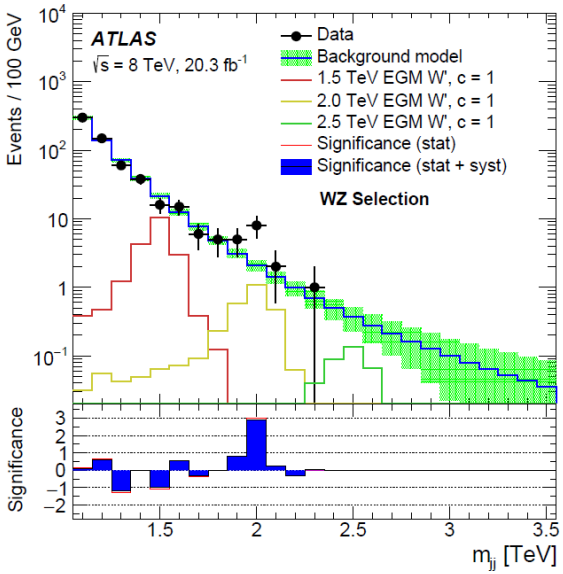
- ATLAS sees $2.5\,\sigma$ excess @ $m_{V'} \simeq 2.0\,\text{TeV}$ for fully hadronic $W' \to WZ$ [8] (significance decreases in combination with other channels [9])
- CMS sees $1.9\,\sigma$ excess @ $m_{V'} \simeq 1.8\,\text{TeV}$ for $W' \to WH \to \ell\nu bb$ [10]

Run 1 $V' \to VH$ analysis in ATLAS [11]

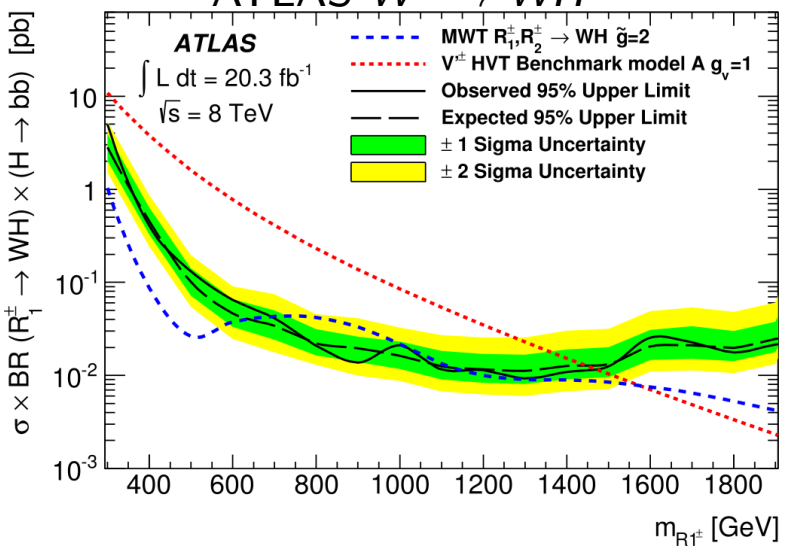
- No excess observed, expected limits degrading above $m_{V'} = 1.3\,\text{TeV}$
- Less sensitivity for higher masses due to a "resolved" jet analyses

For Run 2: Use "boosted" jet selection, reconstruct both b-quarks within one jet

ATLAS $W' \to WZ$

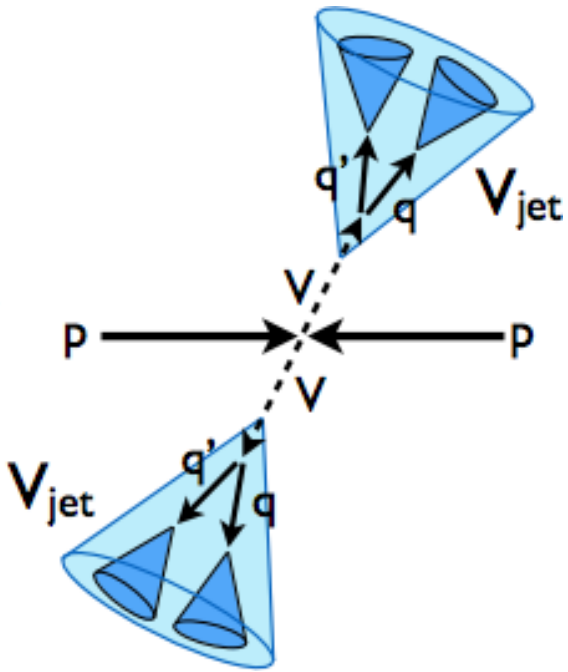


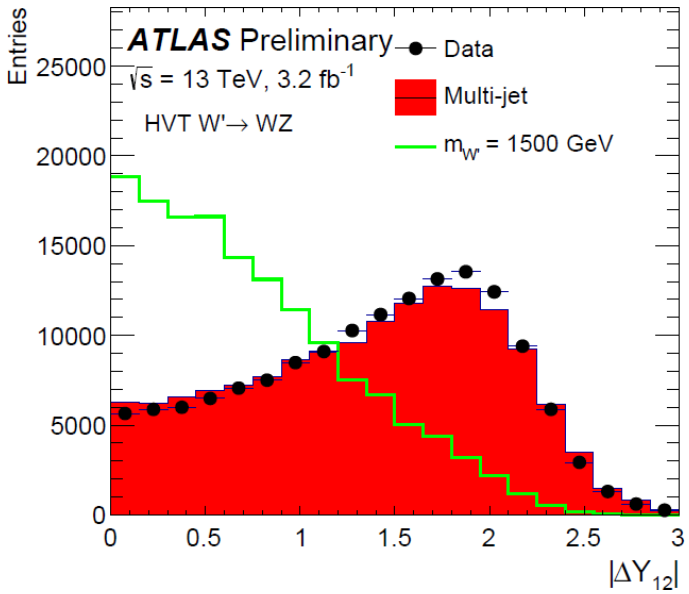
ATLAS $W' \to WH$



$VV \to qqqq$: selection

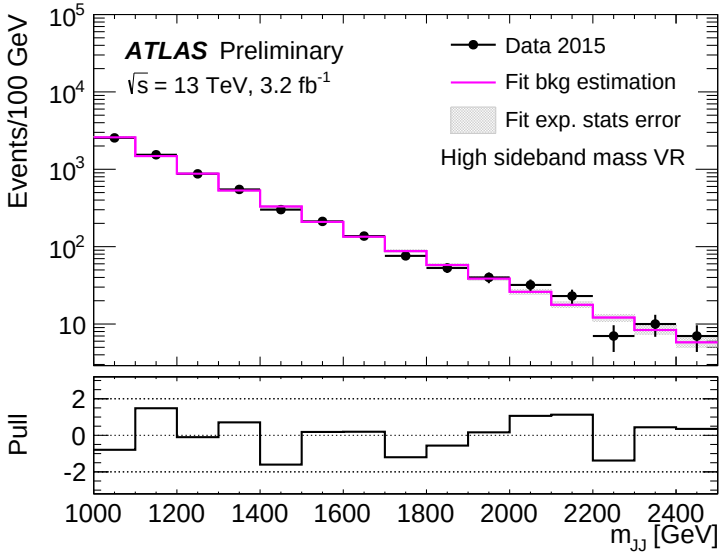
- All hadronic final state $\Rightarrow$ dominant bkg is QCD multi-jet
- 2 large (R=1.0) anti-kt jets (groomed), $p_T^{J1(2)} > 450(200)$ GeV
- $V \to qq$ tagger @ 50% efficiency based on D_2, m_J: QCD rej. factor 40 to 70 per jet
- N_{track} cut: 70% QCD rejection, 30% signal loss
- $|y_1 - y_2| < 1.2$, p_T asymmetry < 0.15
- 3 overlapping signal regions WZ, WW, ZZ (based on $m_{J1,2}$)

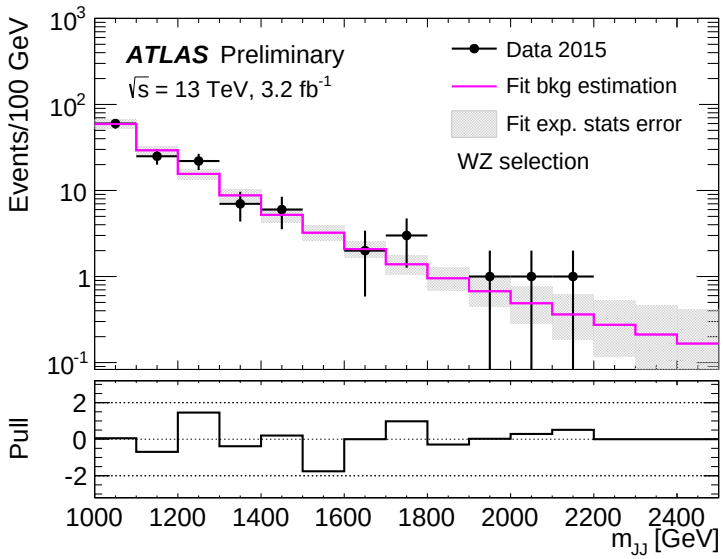


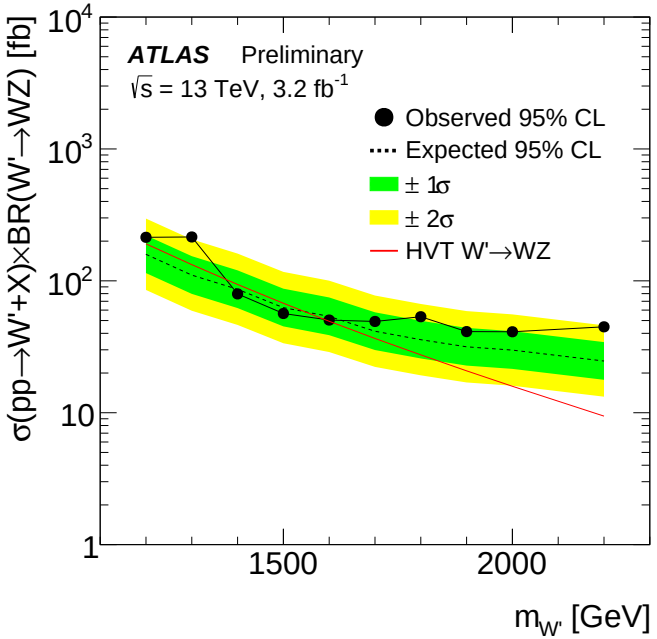


$VV \to qqqq$: results

- Fit m_{JJ} in data with power-law function $\frac{dn}{dx} = p_1(1-x)^{p_2+\xi p_3} x^{p_3} \quad x = \frac{m_{JJ}}{13\,\text{TeV}}$
- Tested on dijet MC and data control regions
- No significant deviations found
- Limits set on HVT and RSG
- 95% CL exclusion (HVT model A, $g_V = 1$): $1.38 < m_{W'} < 1.6\,\text{TeV}$

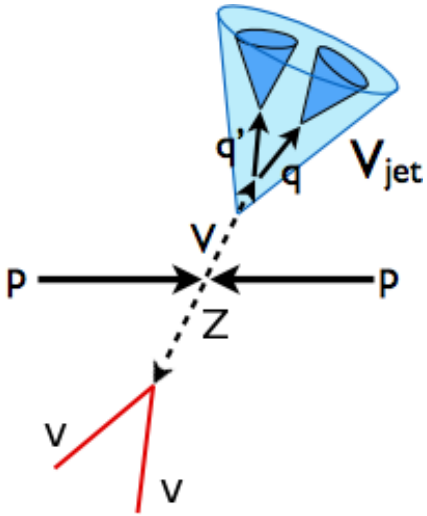






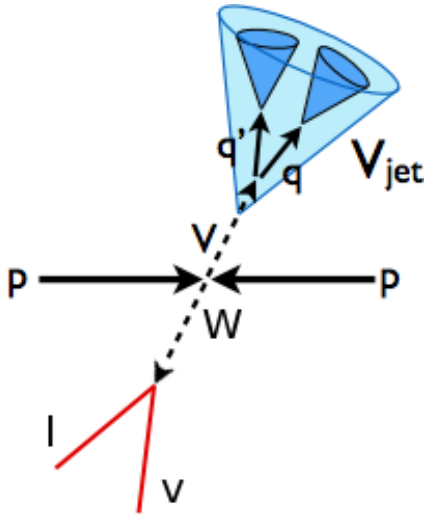
$VV \to \nu\nu qq$, $\ell\nu qq$, $\ell\ell qq$: selection

- Events selected with $p_{\mathrm{T}}^{J} > 200\,\mathrm{GeV}$
- Boson tag (m_J, D_2) @ 50% efficiency



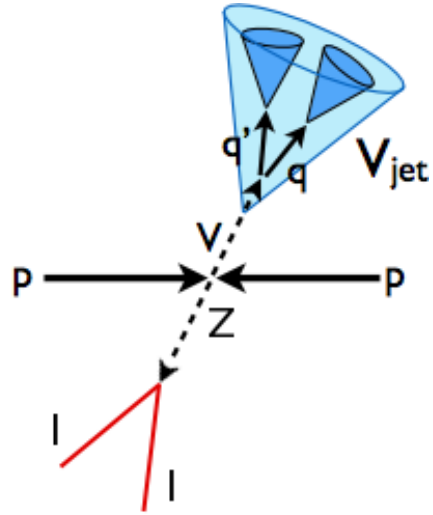
Bkgs: multijet, V+jets, $t\bar{t}$

- 0 leptons
- $E_{\mathrm{T}}^{miss} > 250\,\mathrm{GeV}$
- E_{T}^{miss}, p_{T}^{miss}, jets angular cuts
- b-jet veto



Bkgs: W+jets, multijet, $t\bar{t}$

- 1 lepton
- $E_{\mathrm{T}}^{miss} > 100\,\mathrm{GeV}$
- $p_{\mathrm{T}}^{W,J} > 0.4 m_{lvJ}$
- b-jet veto



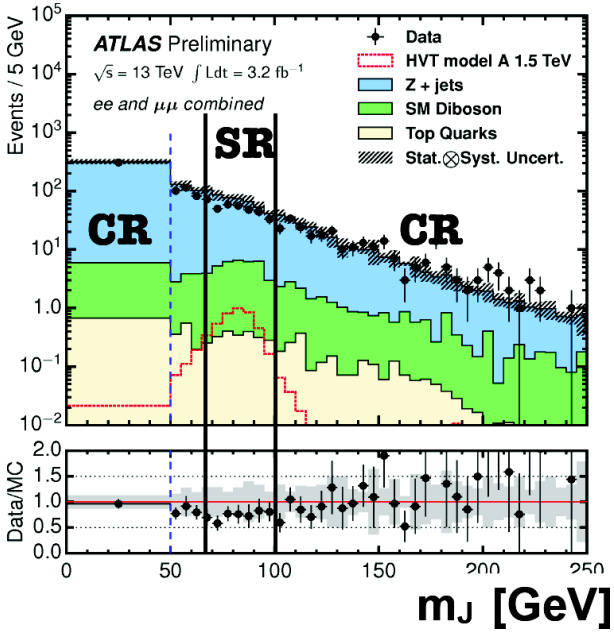
Bkgs: Z+jets

- 2 leptons
- $p_{\mathrm{T}}^{Z,J} > 0.4 m_{llJ}$

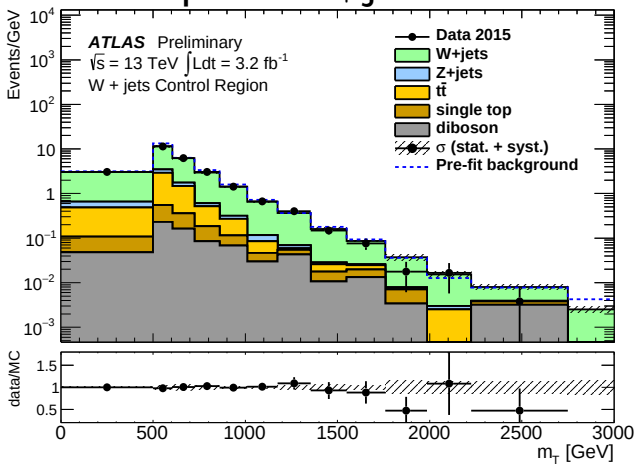
$VV \to \nu\nu qq$, $\ell\nu qq$, $\ell\ell qq$: control regions

Backgrounds estimated from MC and checked in control regions (CRs):

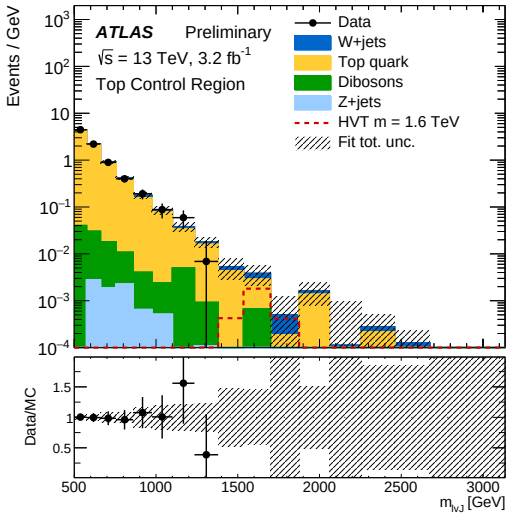
- Jet mass sidebands for W/Z+jets
- Additional b-tags for ttbar
- CRs included in the final fit
  $\Rightarrow$ constrain normalization



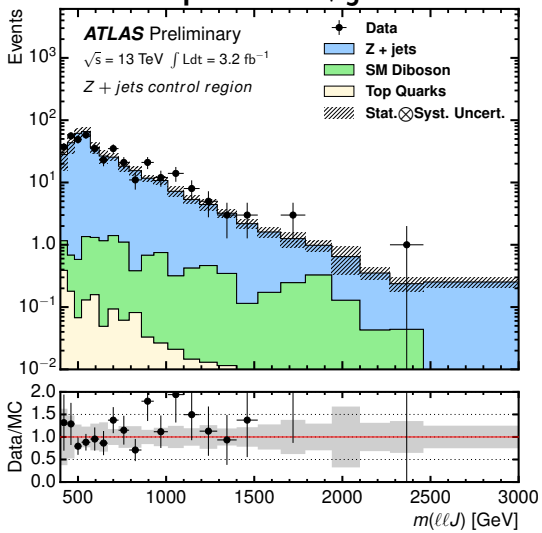
0-lepton W+jets CR



1-lepton top CR

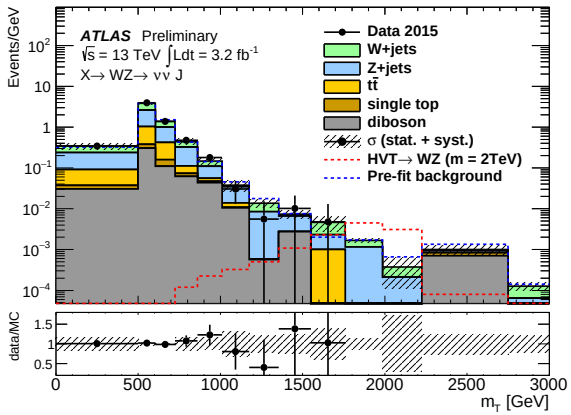


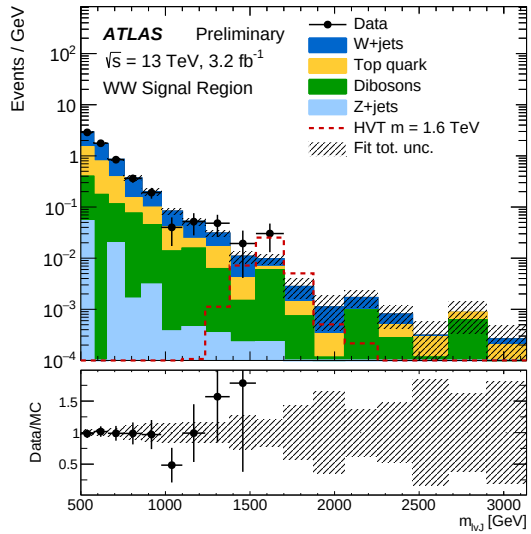
2-lepton Z+jets CR

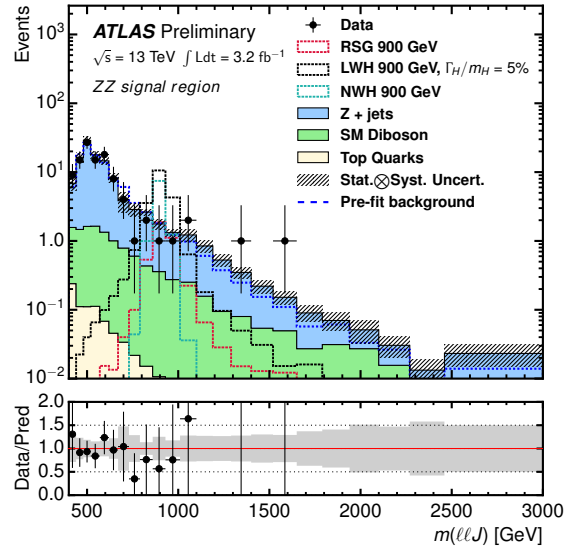


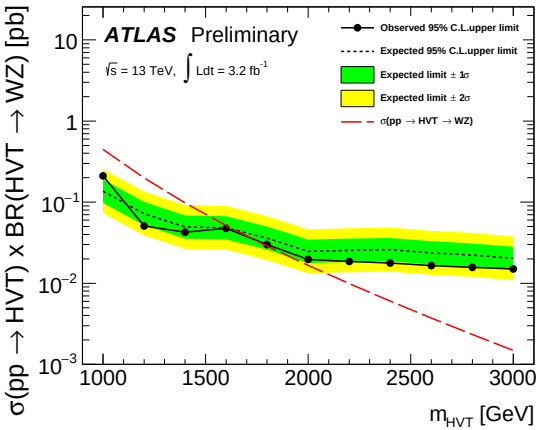
$VV \to \nu\nu qq$, $\ell\nu qq$, $\ell\ell qq$: results

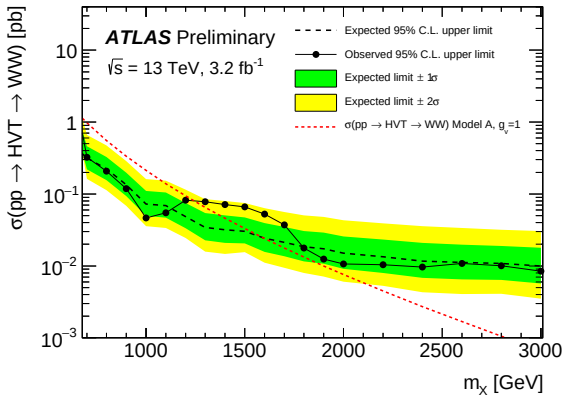
- No significant deviation over the SM backgrounds in m_{VV} spectra
- Limits are set, interpretations: HVT, RSG, Heavy Higgs

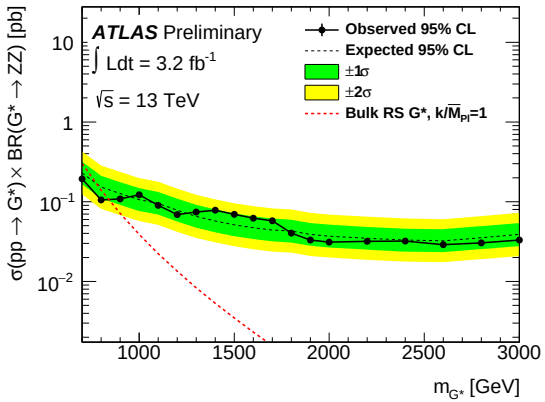




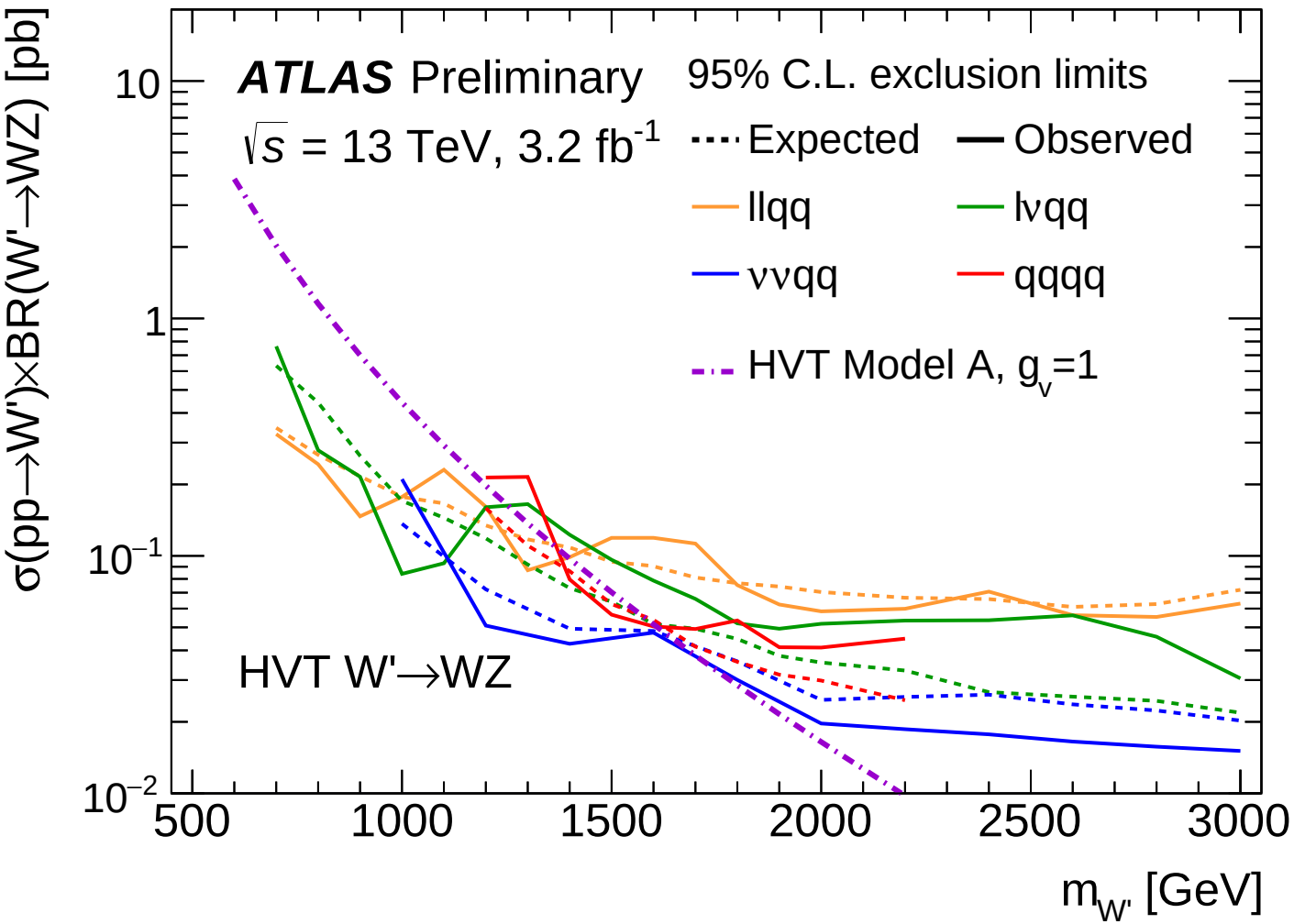








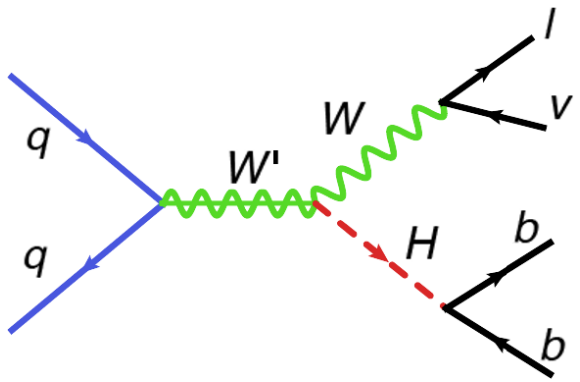
$VV \to \nu\nu qq$, $\ell\nu qq$, $\ell\ell qq$, $qqqq$: summary

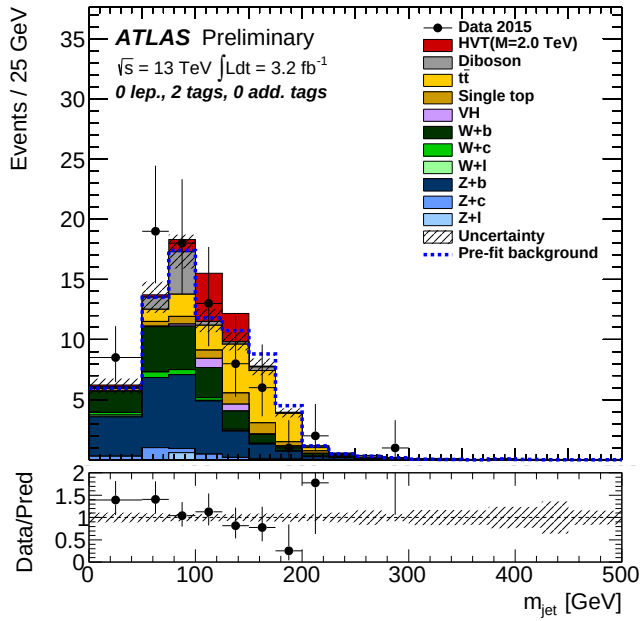


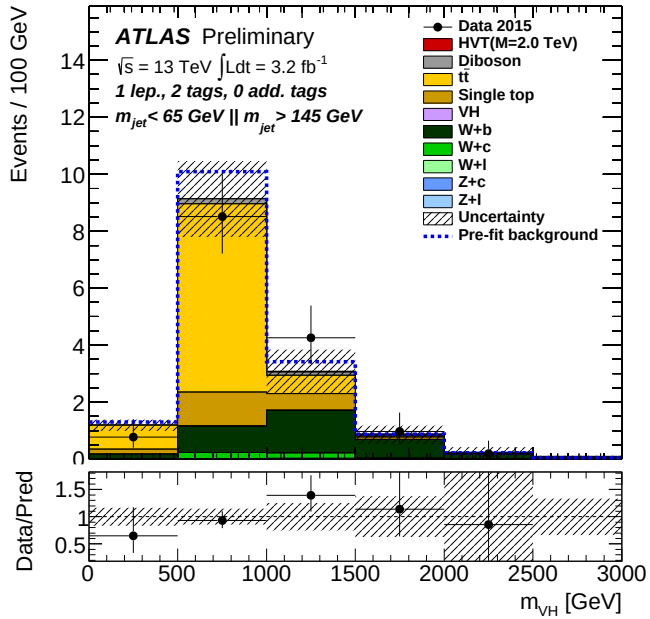
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS/

$VH(\rightarrow bb)$: selection

- Search in $\nu\nu$, $\ell\nu$, $\ell\ell$ channels
- Large jet with $p_T^J > 250$ GeV, $m_J \simeq m_H$
- 1 or 2 b-tags (track-jet assoc. to lead. jet)
- 1ℓ and 2ℓ selected with isol. leptons, 0ℓ with $E_T^{miss} > 200$ GeV
- Main bkgs.: Z+jets (0ℓ, 2ℓ) and W+jets, ttbar (1ℓ)
- Fit to m_{VH} in signal and control regions (m_J sidebands and $N_{btag}^{add} \geq 1$)

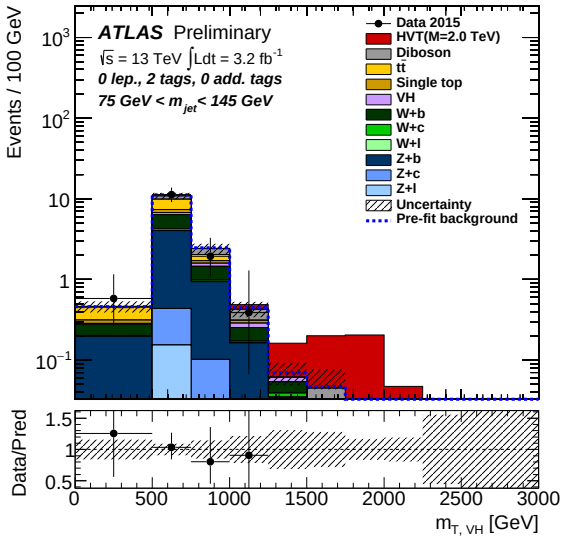


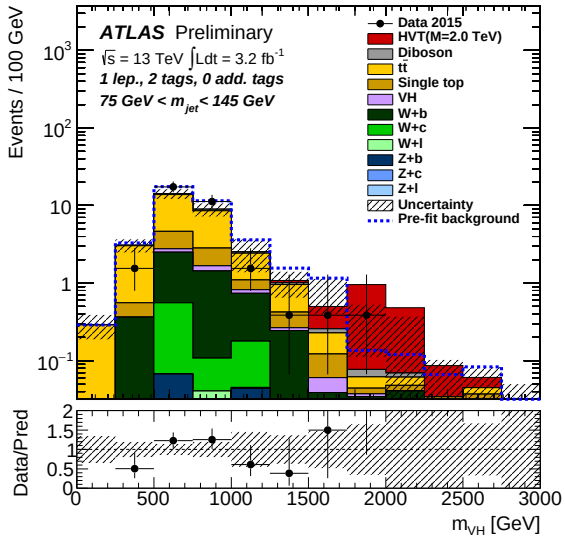


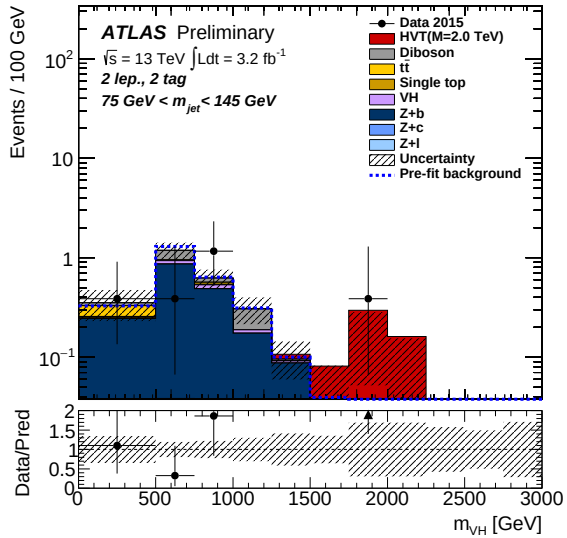


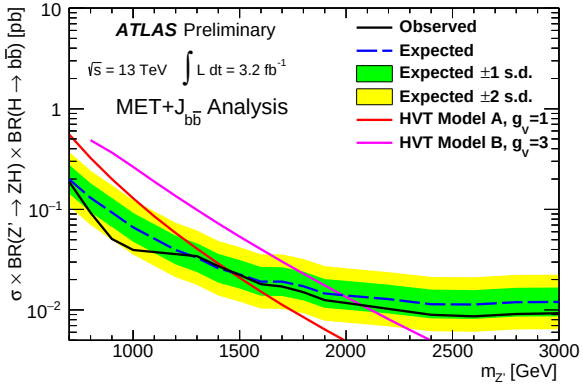
$VH(\rightarrow b\bar{b})$: results

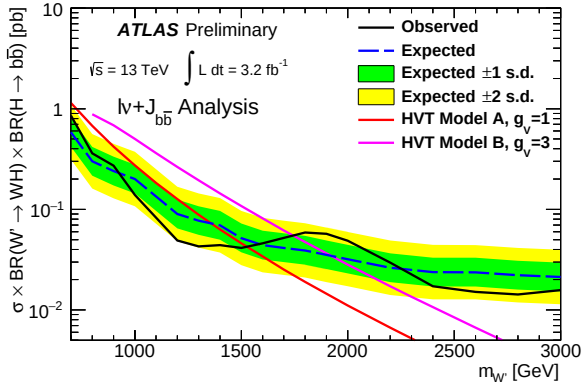
- No significant deviation over the SM backgrounds in m_{VH} spectrum
- Limits are set, interpretation: HVT

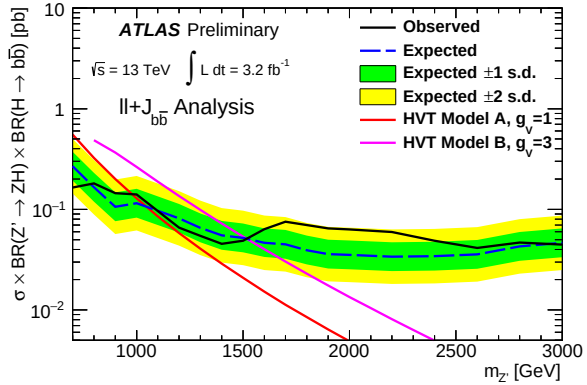












$\gamma\gamma$: Selection

Pre-selection

- Two photons with tight identification and isolation criteria
- Precision region of EM calorimeter: $|\eta| < 2.37$ (1.37-1.52 excluded)

Spin-0 analysis

Optimized for Higgs-like signal

- $E_{\mathrm{T}}^{\gamma 1} > 0.4 m_{\gamma\gamma}$, $E_{\mathrm{T}}^{\gamma 2} > 0.3 m_{\gamma\gamma}$

$\Rightarrow$ +20% significance for $m_X > 600\,\mathrm{GeV}$, effectively deplete forward regions

As model-independent as possible

- Limit on fiducial cross section

Search range

- $m_X = [200 GeV - 2 TeV]$
- $\Gamma_X / m_X = [0\% - 10\%]$

Spin-2 analysis

Loose selection

- $E_{\mathrm{T}}^{\gamma 1,2} > 55\,\mathrm{GeV}$

$\Rightarrow$ Preserve acceptance at high mass

- Use RS graviton as benchmark

Search range

- $m_X = [500 GeV - 3 TeV]$
- $k/M_{Pl} = [0.01 - 0.3]$
- $\Gamma_X / m_X \simeq 1.44 (k/\overline{M}_{Pl})^2 \simeq [0\% - 10\%]$

$\gamma\gamma$: Background fit

Spin-0 analysis

Functional background form

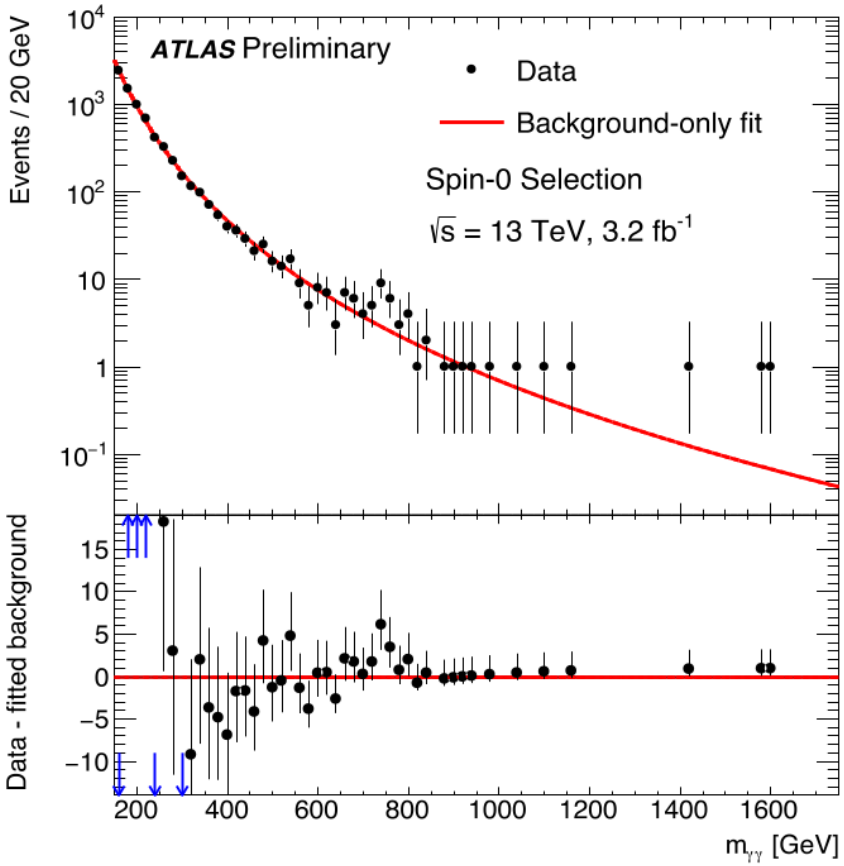
- Family of nested functions (power law $\times$ log polynomials)
- Needed d.o.f. determined from F-test

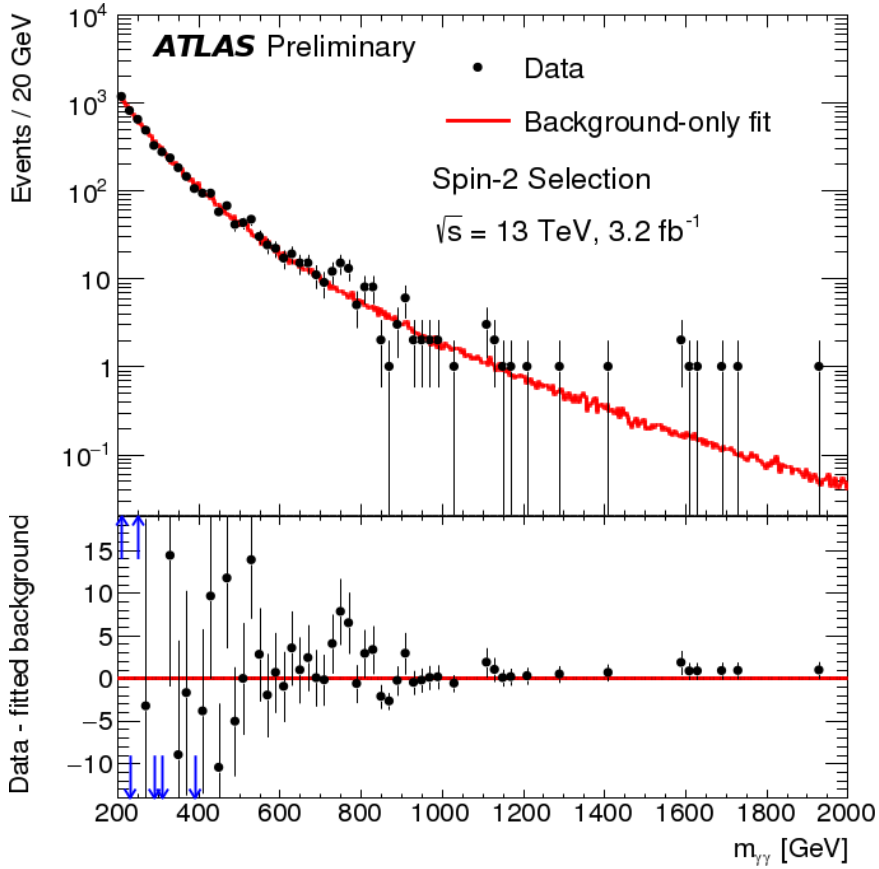
Spin-2 analysis

Irreducible bkg ($\gamma\gamma$) from MC

- SHERPA $\gamma\gamma$ including detector sim, reweighted to DIPHOX NLO $m_{\gamma\gamma}$

Reducible ($\sim 10\,\%$ γj, $< 1\,\%$ jj) from data





$\gamma\gamma$: Results

Spin-0 analysis

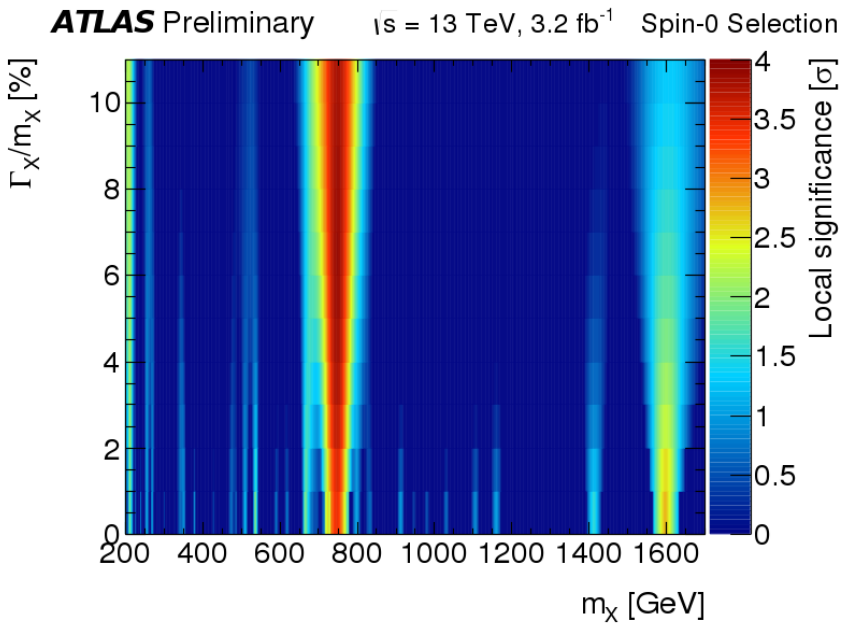
Largest deviation from B-only hypothesis

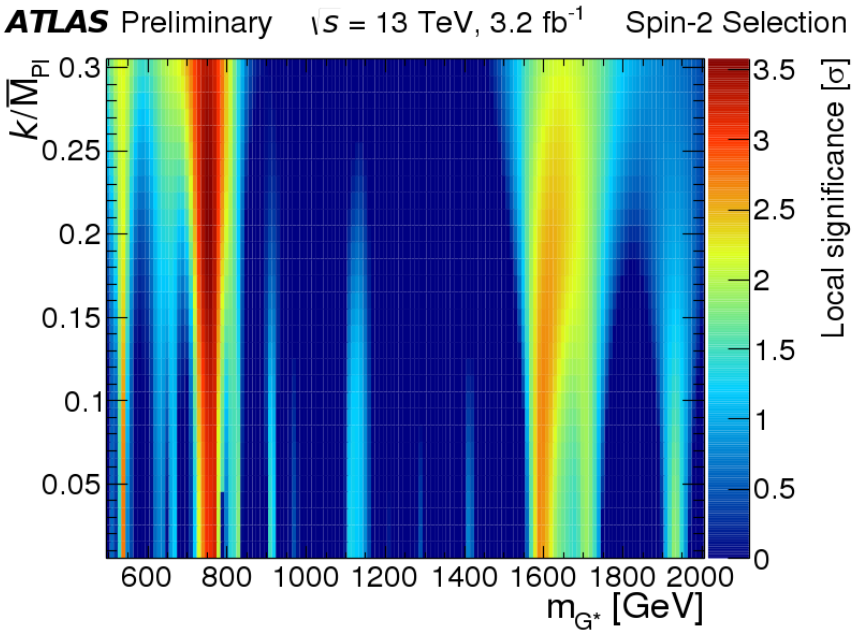
- $m_X \simeq 750\,\text{GeV}$, $\Gamma_X/m_X \simeq 6\,\%$
- Local $Z = 3.9\,\sigma$ ($3.5\,\sigma$ for $\Gamma_X \simeq 0$)
- Global $Z = 2.0\,\sigma$ (search range)

Spin-2 analysis

Largest deviation from B-only hypothesis

- $m_X \simeq 750\,\text{GeV}$, $\Gamma_X/m_X \simeq 6\,\%$ ($k/M_{Pl} \simeq 0.2$)
- Local $Z = 3.6\,\sigma$
- Global $Z = 1.8\,\sigma$ (search range)





$\gamma\gamma$: Re-analysis of 8 TeV data

Spin-0 analysis

- $1.9\,\sigma$ at $m_X = 750\,\text{GeV}$, $\theta_X/m_X = 6\,\%$

Compatibility with 13 TeV spin-0 analysis

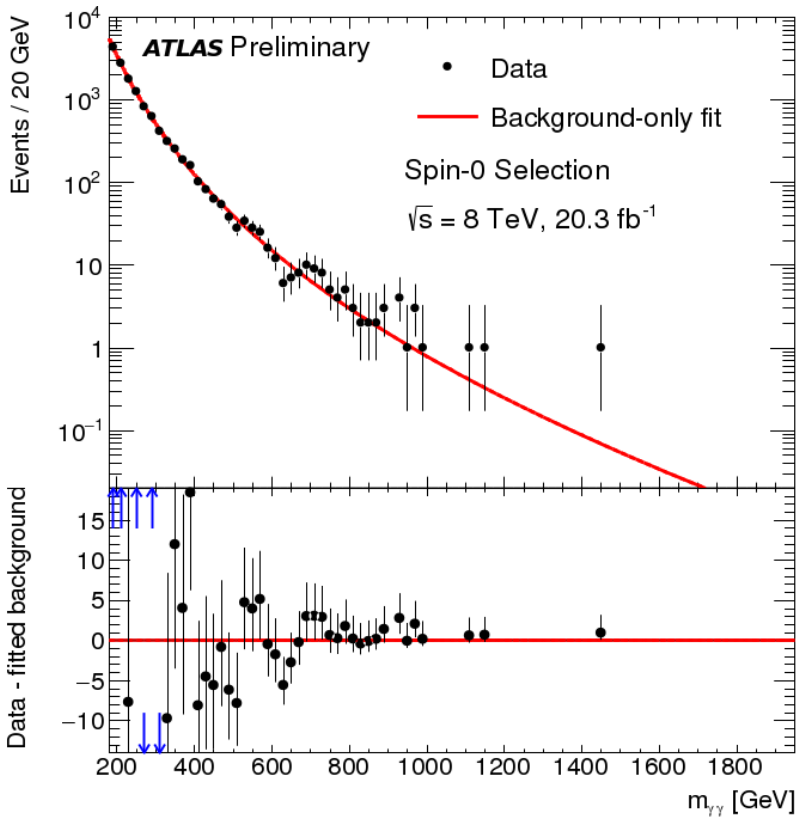
- gg (scaling: 4.7) $\rightarrow 1.2\,\sigma$
- qq (scaling: 2.7) $\rightarrow 2.1\,\sigma$

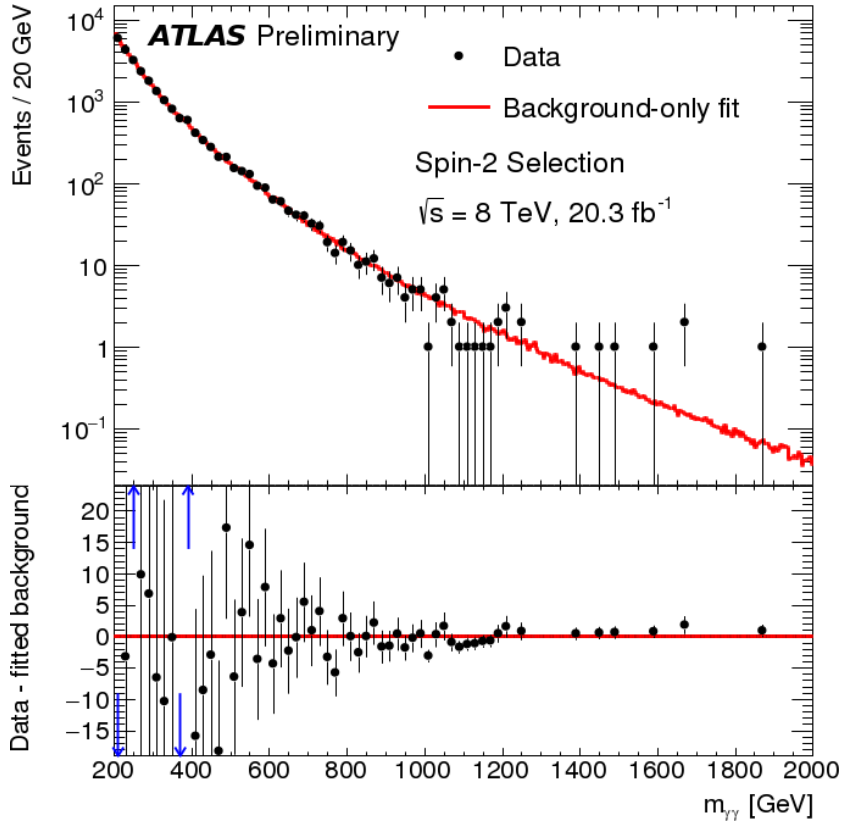
Spin-2 analysis

- No significant excess

Compatibility with 13 TeV spin-2 analysis

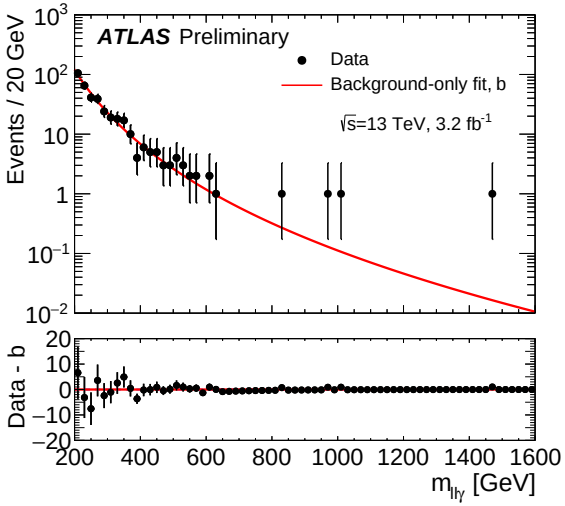
- gg $\rightarrow 2.7\,\sigma$
- qq $\rightarrow 3.3\,\sigma$

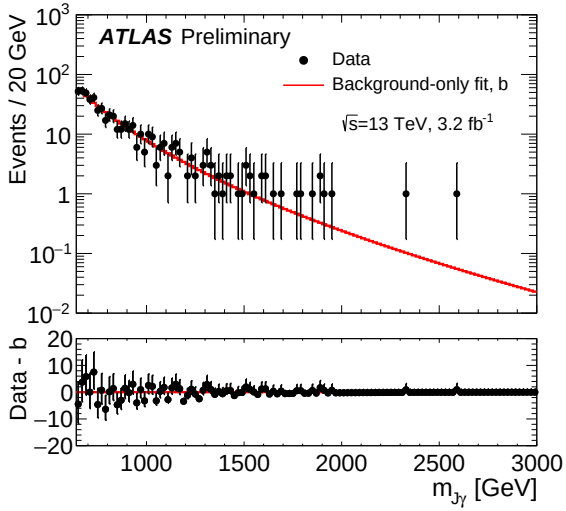


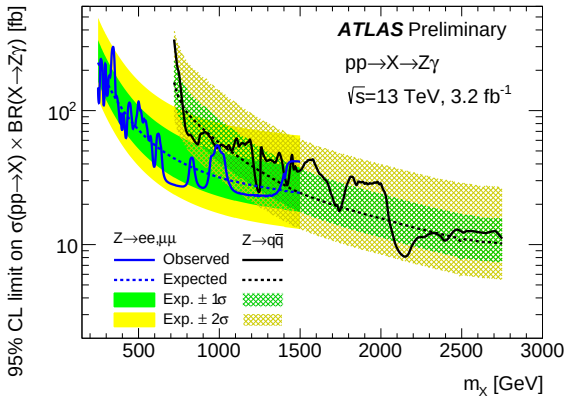


$Z\gamma$ analysis

- $Z\gamma$ resocance search: interesting in regard of possible $\gamma\gamma$ signal
- $Z(\to \ell\ell)\gamma$ analysis: search range $m_X = 0.25$ to $1.5\,\text{TeV}$
  $E_T^\gamma > 0.3 m_X$, $p_T^\ell > 10\,\text{GeV}$, $m_{\ell\ell} - m_Z < 15\,\text{GeV}$
- $Z(\to qq)\gamma$ analysis: search range $m_X = 0.72$ to $2.75\,\text{TeV}$
  $E_T^\gamma > 250\,\text{GeV}$, $p_T^J > 200\,\text{GeV}$, $80 < m_J < 110\,\text{GeV}$
- Analytic background model similar to $\gamma\gamma$
- No excess observed, limits are set (heavy Higgs)







Summary

Searches for diboson resonances performed with $\sqrt{s} = 13\,\text{TeV}$, $3.2\,\text{fb}^{-1}$ data

- Most searches do not see significant excesses, limits are set
  $\rightarrow$ Exceeding Run 1 sensitivity for high masses
- Largest excess observed in $\gamma\gamma$ resonance search around $m_X = 750\,\text{GeV}$
  $\rightarrow$ Global significance $2.0\,\sigma$ ($1.8\,\sigma$) for the spin-0 (spin-2) analysis
- 8 TeV $\gamma\gamma$ data re-analyzed, compatibility with 13 TeV results assessed
  $\rightarrow$ gg: $1.2\,\sigma$ ($2.7\,\sigma$), qq: $2.1\,\sigma$ ($3.3\,\sigma$) for the spin-0 (spin-2) analysis

Looking forward to 2016 LHC run for more data!

BACKUP

References I

[1] *Search for resonances with boson-tagged jets in 3.2 fb1 of p p collisions at $s = 13$ TeV collected with the ATLAS detector*, Tech. Rep. ATLAS-CONF-2015-073, CERN, Geneva, Dec, 2015.
https://cds.cern.ch/record/2114845.

[2] *Search for diboson resonances in the $\nu\nu qq$ final state in pp collisions at $\sqrt{s}$ =13 TeV with the ATLAS detector*, Tech. Rep. ATLAS-CONF-2015-068, CERN, Geneva, Dec, 2015.
https://cds.cern.ch/record/2114840.

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$\gamma\gamma$: Photon energy calibration

MV regression to calibrate photon cluster energy (EPJ C74 (2014) 3071)

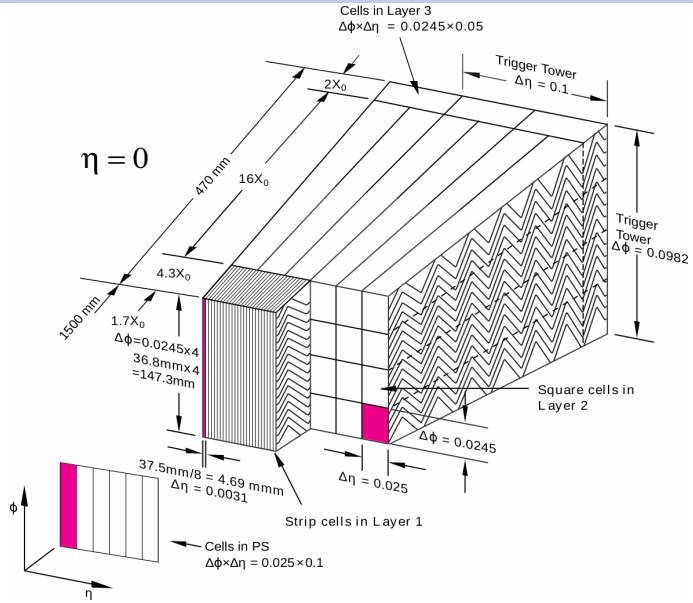
- EMC longitudinal layers inter-calibration from from 2012 data
- \+ additional uncertainty (mostly affecting constant term)
- Energy scale and resolution corrections checked with 13 TeV $Z \to ee$ events

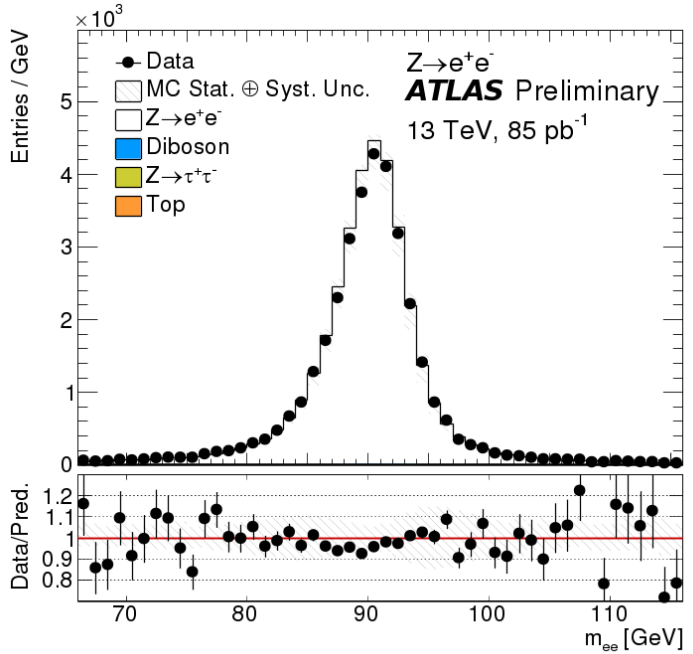
At $E_{\mathrm{T}}^{\gamma} > 100$-200 GeV, resolution dominated by constant term $c = 0.6\,\%$ - $1.5\,\%$

- $\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$

Uncertainties

- Energy scale: $\pm(0.4\,\%$ - $2\,\%)$
- Energy resolution ($E_{\mathrm{T}}^{\gamma} = 300\,\mathrm{GeV}$): $\pm(80\,\%$ - $100\,\%)$





$\gamma\gamma$: Signal modeling

Spin-0 analysis

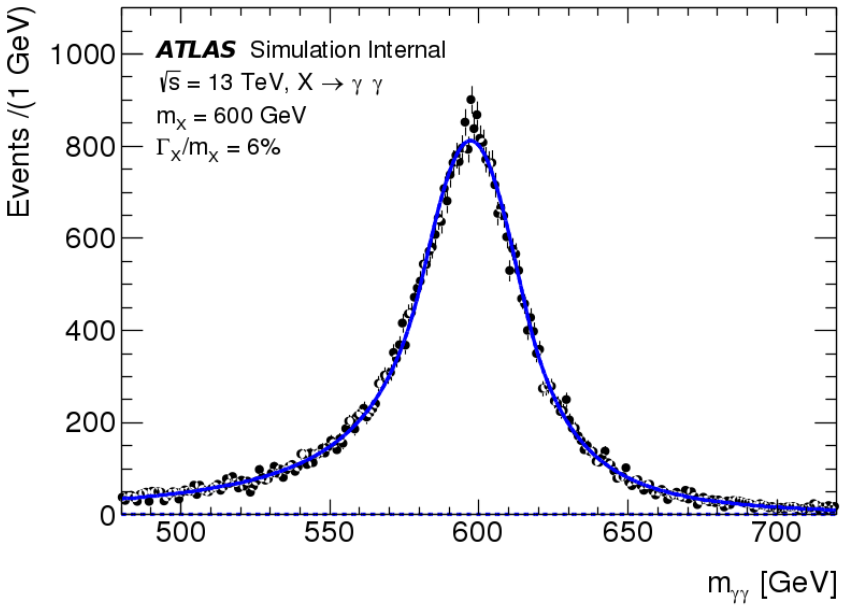
Heavy Higgs-like model

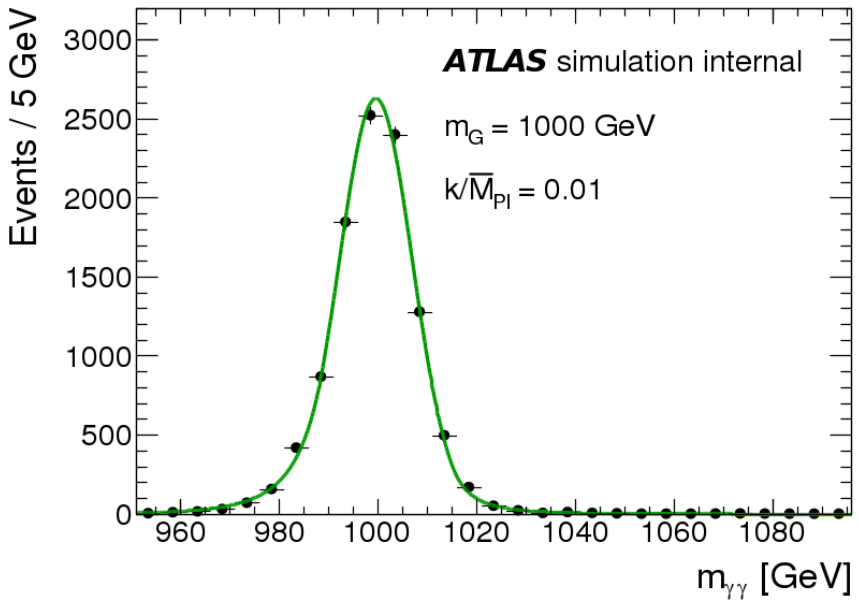
- Narrow to large width ($\Gamma_X = 4\,\text{MeV}$ to $10\,\% m_X$)
- Powheg line-shape assuming SM couplings convoluted to detector response (ggF)
- Double-Sided Crystal Ball (DSCB)

Spin-2 analysis

RS-graviton-like model

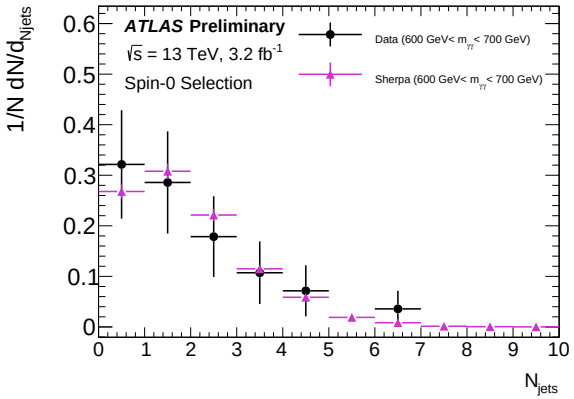
- $k/M_{Pl} = 0.01$ ($\gamma_G/m_G = 0.01\,\%$) to measure and parameterize detector response (DSCB)
- Analytical convolution of theoretical line-shape with detector response

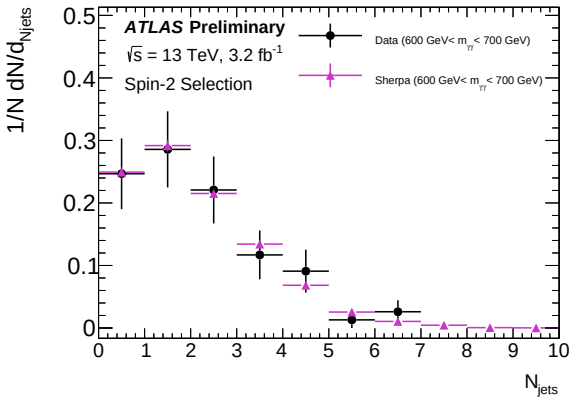




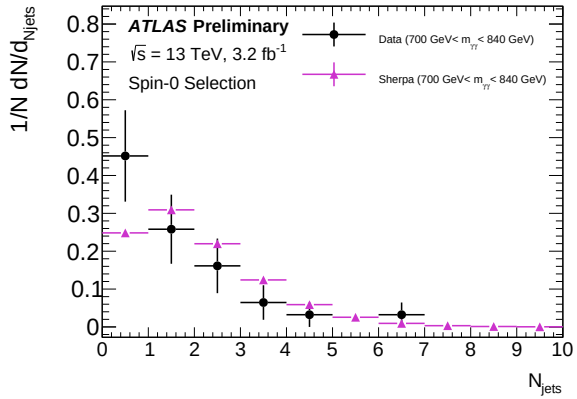
$\gamma\gamma$ plots: N_{jet}

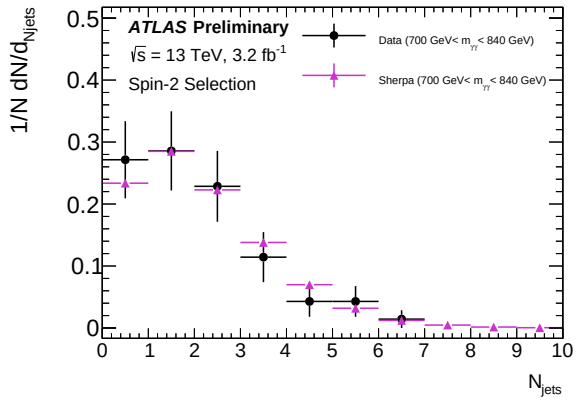
$600 < m_{\gamma\gamma} < 700$ GeV



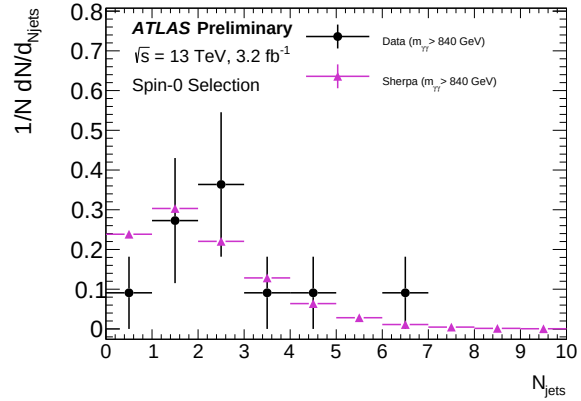


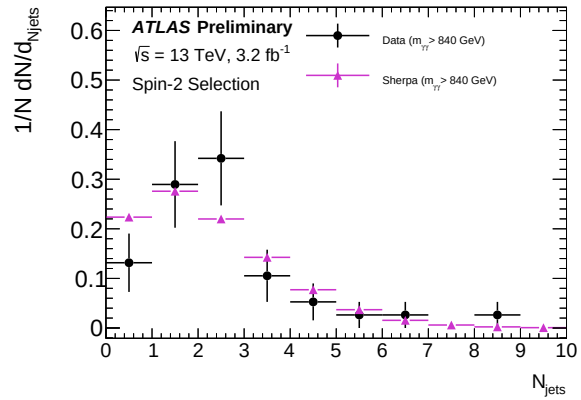
$700 < m_{\gamma\gamma} < 840$ GeV





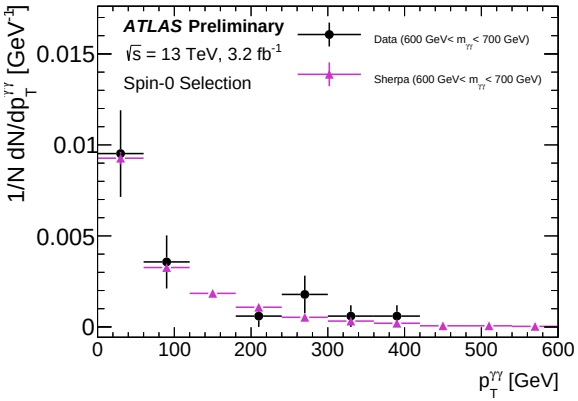
$m_{\gamma\gamma} > 840$ GeV

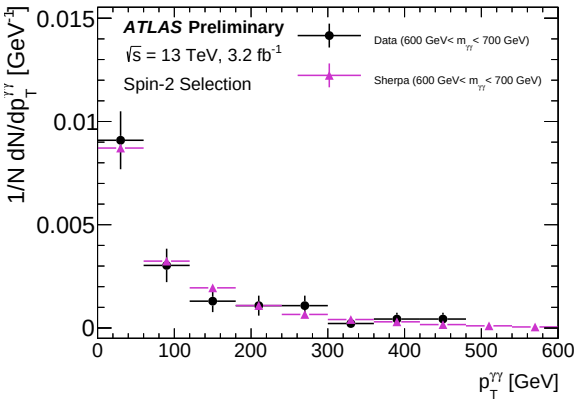




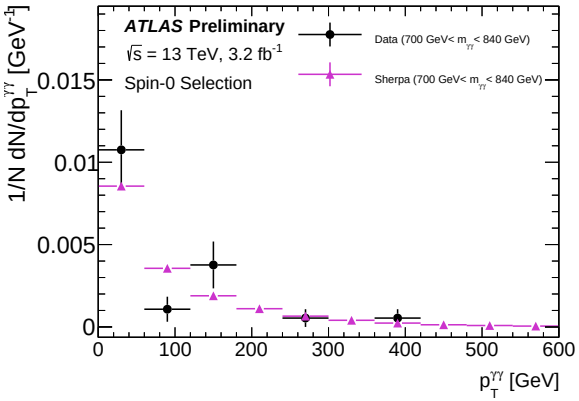
$\gamma\gamma$ plots: $p_T^{\gamma\gamma}$

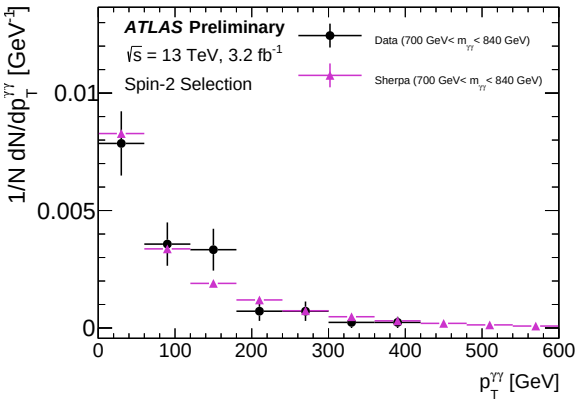
$600 < m_{\gamma\gamma} < 700$ GeV



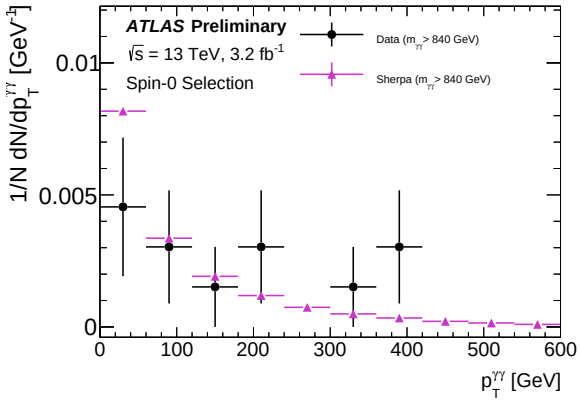


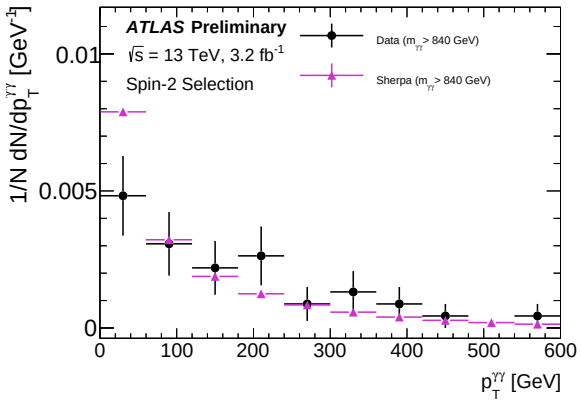
$700 < m_{\gamma\gamma} < 840$ GeV





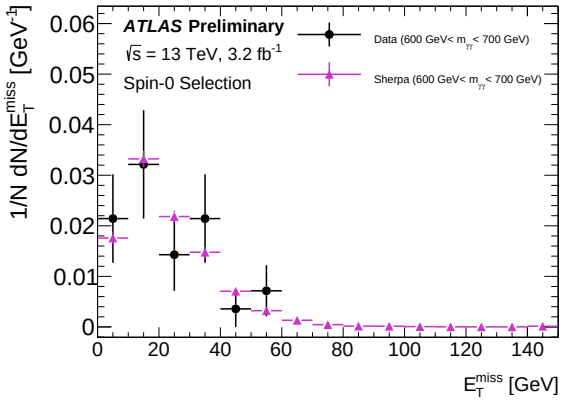
$m_{\gamma\gamma} > 840$ GeV

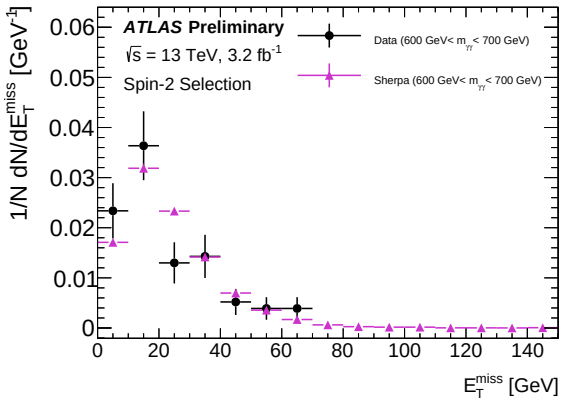




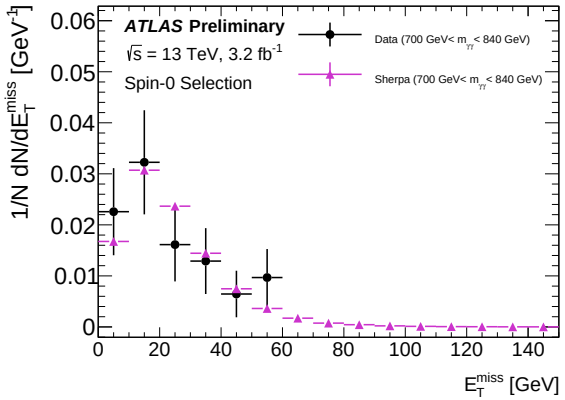
$\gamma\gamma$ plots: E_T^{miss}

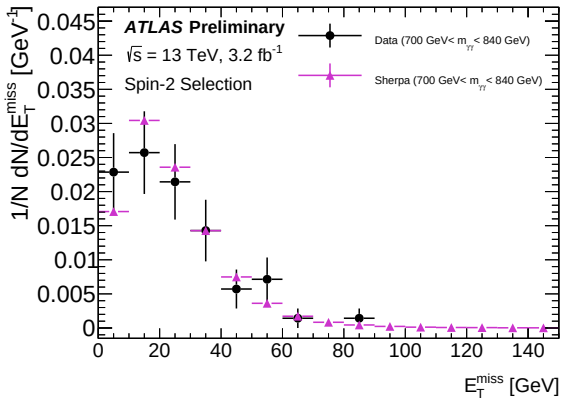
$600 < m_{\gamma\gamma} < 700$ GeV



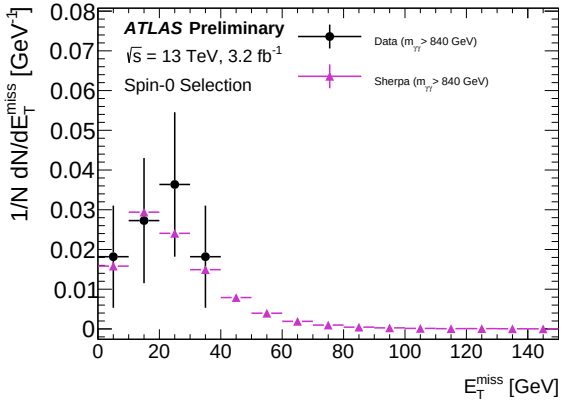


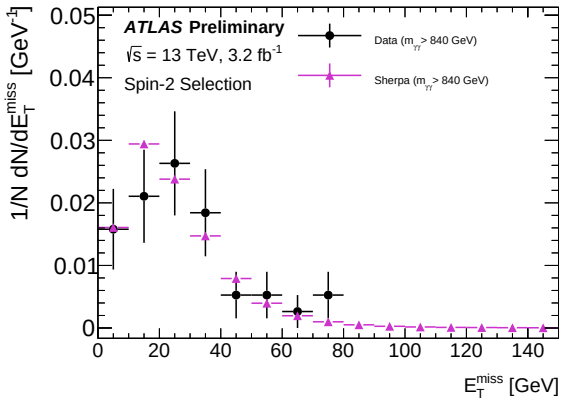
$700 < m_{\gamma\gamma} < 840$ GeV





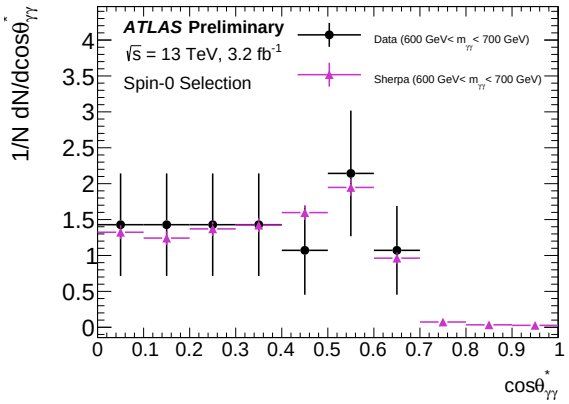
$m_{\gamma\gamma} > 840$ GeV

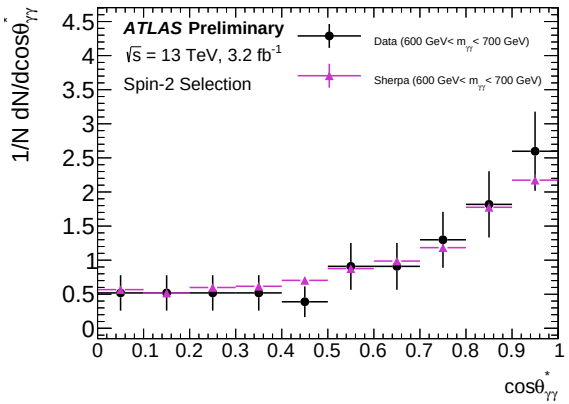




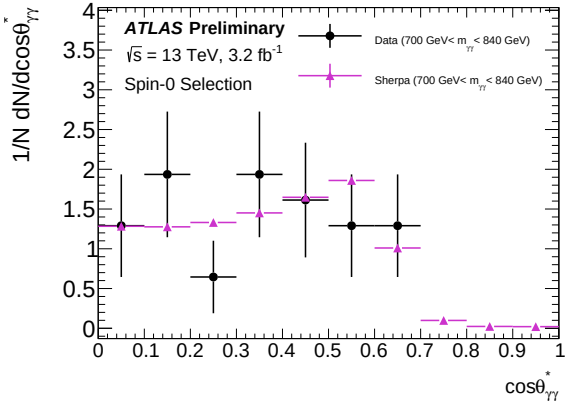
$\gamma\gamma$ plots: $\cos\theta^*_{\gamma\gamma}$

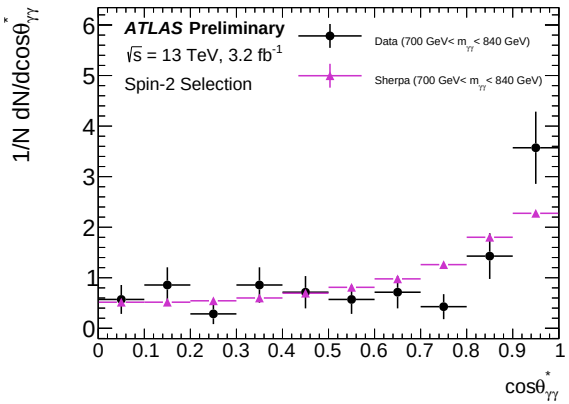
$600 < m_{\gamma\gamma} < 700$ GeV





$700 < m_{\gamma\gamma} < 840$ GeV





$m_{\gamma\gamma} > 840$ GeV