Searches for New Physics with Bosons at the ATLAS Detector in LHC Run II

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ATLAS
EXPERIMENT

Introduction

- Large Hadron Collider (LHC) Run I data allowed the Higgs discovery, a plethora of precision measurements and limit setting on other models beyond the Standard Model (SM)

- Run I results show no (significant) indication of new physics

- However the SM does not provide answers to a large number of open issues, e.g.
  - *Gravity*
  - *Dark matter/energy*
  - *Hierarchy problem*

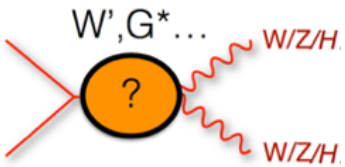
- Unanswered questions motivate further searches, either SUSY or Exotics

- Run II: the center of mass energy ($\sqrt{s}$) increased from 8 TeV to 13 TeV $\rightarrow$ TeV scale searches for new physics

- <u>This talk covers searches for new physics with bosons</u>
  - **VV/Zγ/γγ/Vh/hh** (where V=W/Z, h is SM Higgs boson)
  - Note: Higgs boson is the new tool for searches in addition to the gauge bosons

Why Searches with Bosons?

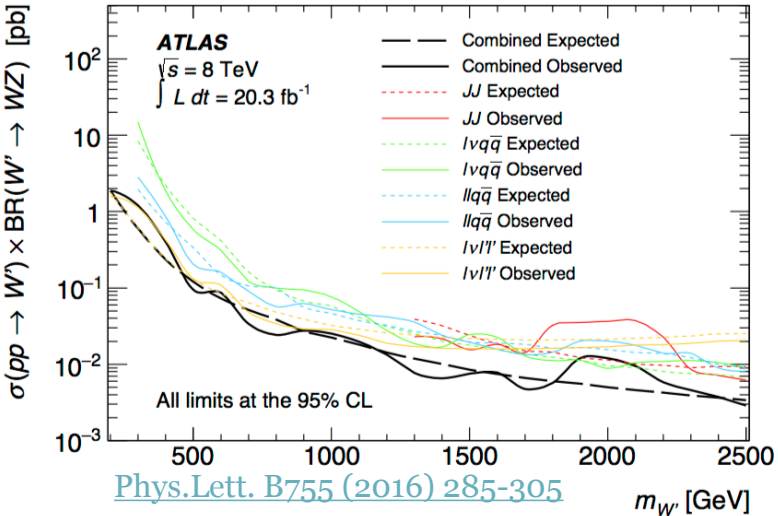
- **Many SM extensions predict new particles decaying into boson pairs**
  - *Wrapped Extra Dimensions*
  - *Grand Unified Theories (GUTs)*
  - *Technicolor*
  - *Two Higgs Doublet Model (2HDM)*
  - *Sequential Standard Model (SSM)*



- **Benchmark scenarios used in the following slides:**
  - Charged final state (WZ)
    - SSM (W', spin 1): *trilinear W'WZ coupling set by Extended Gauge Model*
  - Neutral final state (WW/ZZ/hh)
    - Randall-Sundrum Graviton (RS G*, spin 2): *benchmark model with extra dimensions*
    - Bulk Graviton (Bulk G*, spin 2): *couples more with heavy particles (W/Z/t)*
  - Simplified Lagrangian - Heavy Vector Triplet (HVT)
    - Model A: *weakly coupled vector resonances, from extension of the gauge group*
    - Model B: *produced in a strong scenario, e.g. composite Higgs model*

- **Run I excess seen in the VV full hadronic decay (3.4σ local)**

Model independent searches are important!



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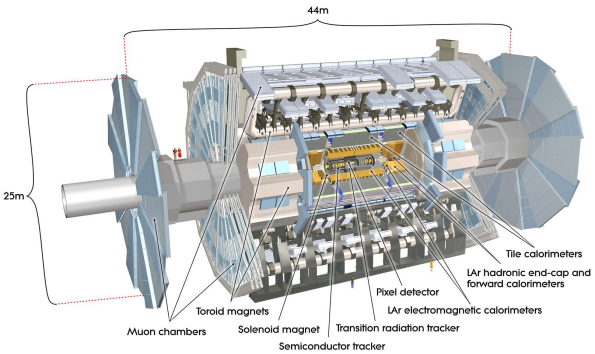
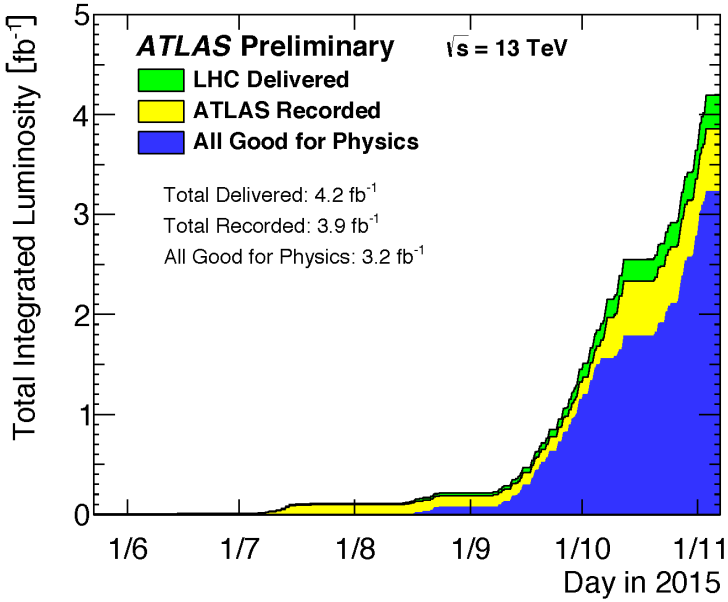
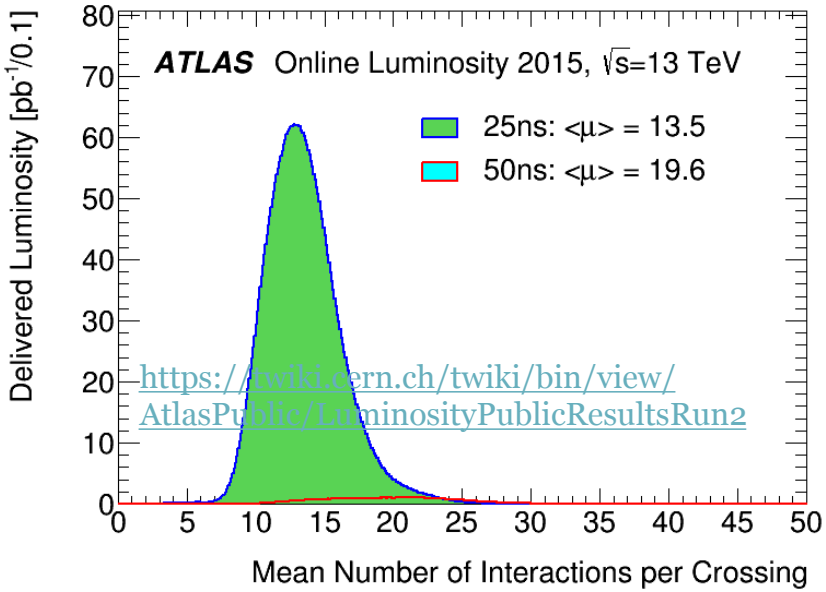


ATLAS @LHC

- LHC Run I delivered 20.3 fb^{-1} at $\sqrt{s}$ = 8 TeV
- Run II at $\sqrt{s}$ = 13 TeV (25 ns bunch spacing) started in 2015
- Delivered 3.2 fb^{-1} of data in 2015 with 93.1% data quality efficiency
- 2016 p-p collisions are starting soon
- ~25 fb^{-1} are expected this year
- Run II goal: ~100 fb^{-1}





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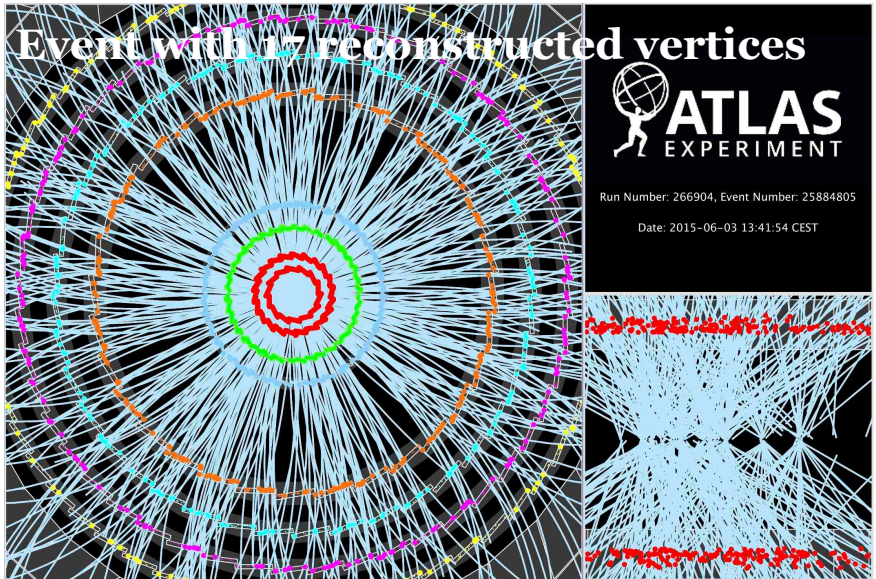


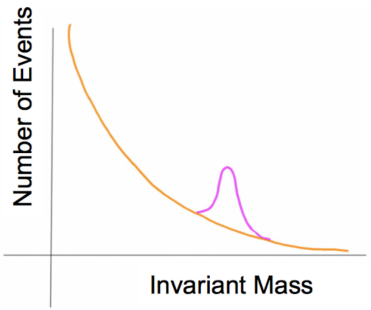
Searches Observables

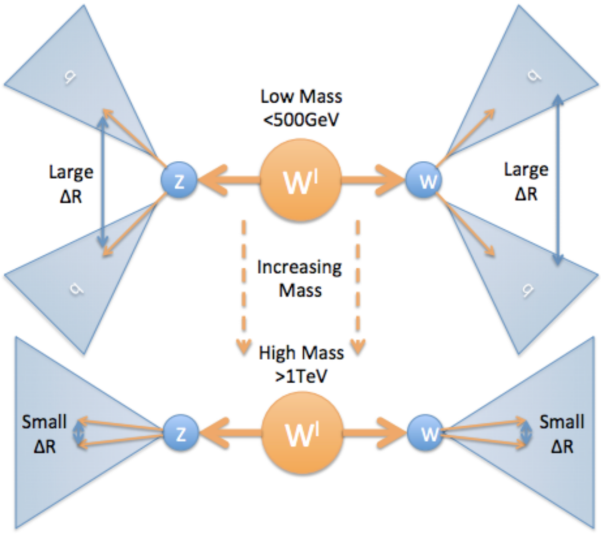
- **Searches methodology:**
  - Look for excesses in mass spectrum

- **Final state decay products can be highly boosted if search particle is very massive**

- **V/h decays considered:**
  - Leptonic (ll, lν, νν)
    - *Small branching ratios*
    - *Cleaner final states through leptons reconstruction*
    - *Performs better at low masses*

  - Hadronic (qq, bb)
    - *Larger branching ratios*
    - *Performs better at high masses where SM backgrounds fall off (mostly X+jets)*
    - *Angular separation ~2m/p_T*
    - *Resolved Regime: relatively low momentum, one small-R jet (distance parameter R = 0.4) is reconstructed for each quark*
    - *Boosted Regime: relatively high momentum, boson is reconstructed as a large-R jet (R = 1.0) - denoted as J*
    - *Novel techniques had to be developed for boosted objects identification*





Boosted Boson Tagging

- **Anti-kt R = 1.0 jets are used**

- Grooming technique (pile-up & soft QCD subtraction):
  - **Trimming** ($p_T^{constituent}/p_T^{jet} < 5\%$)
  - Possible due to the fine calorimeter granularity (ranges from 0.003×0.1 to 0.1×0.1 in Δη×Δφ)

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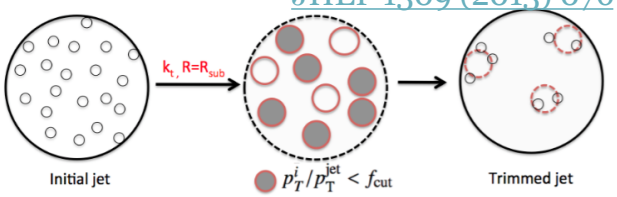

- **Boson tagging**:
  - Jet mass window
  - Energy Correlation Functions (ECF)

$$D_2^{\beta=1} = E_{CF3}\left(\frac{E_{CF1}}{E_{CF2}}\right)^3$$

$$E_{CF1} = \sum_i p_{T,i}$$

$$E_{CF2} = \sum_{ij} p_{T,i} p_{T,j} \Delta R_{ij}$$

$$E_{CF3} = \sum_{ijk} p_{T,i} p_{T,j} p_{T,k} \Delta R_{ij} \Delta R_{jk} \Delta R_{ki}$$

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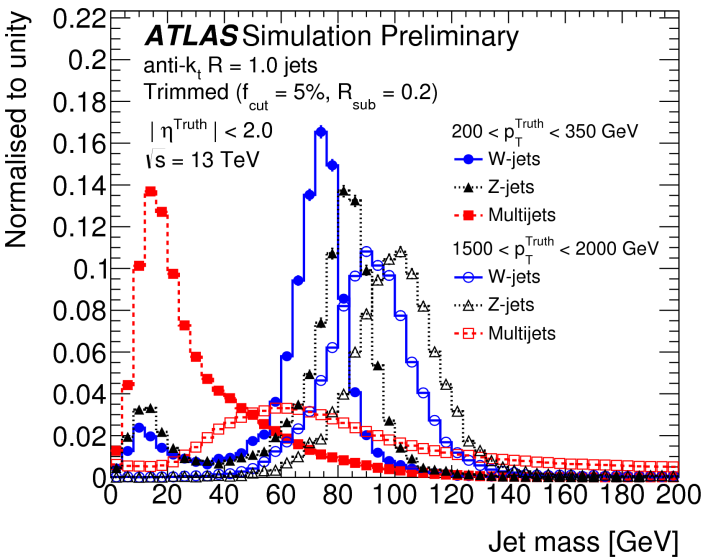

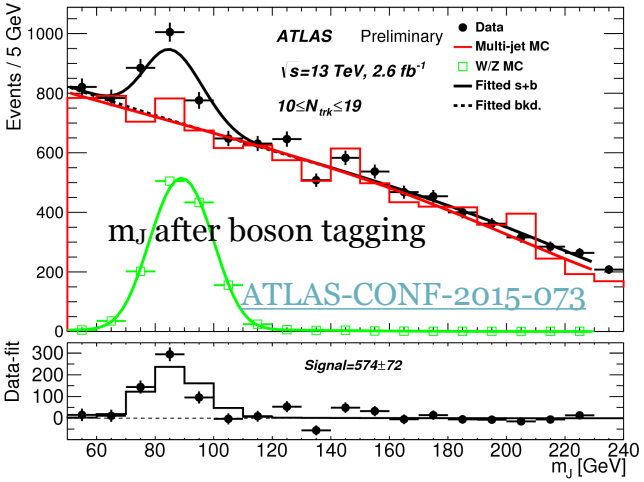

m_J after boson tagging

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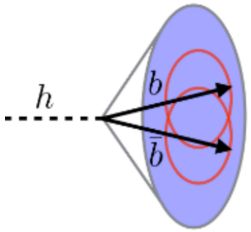
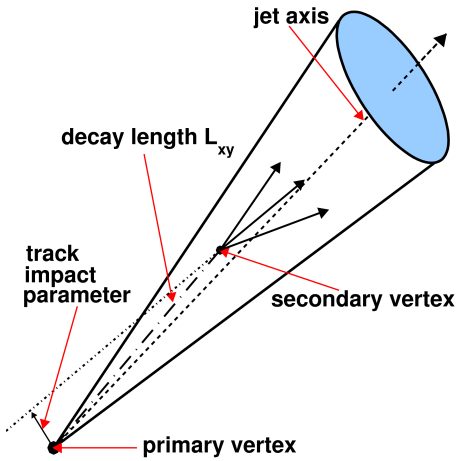
The combination of the above selection provides ~50% signal efficiency vs >90% background rejection



Boosted h→bb Tagging



- Exploit the small-R (R = 0.2) b-jets inside the large-R jet
- b-tagging uses tracks matched to vertices
- Small-R track-jets are used for b-tagging in boosted topologies
- Small-R jet 70% b-tagging efficiency working point is used

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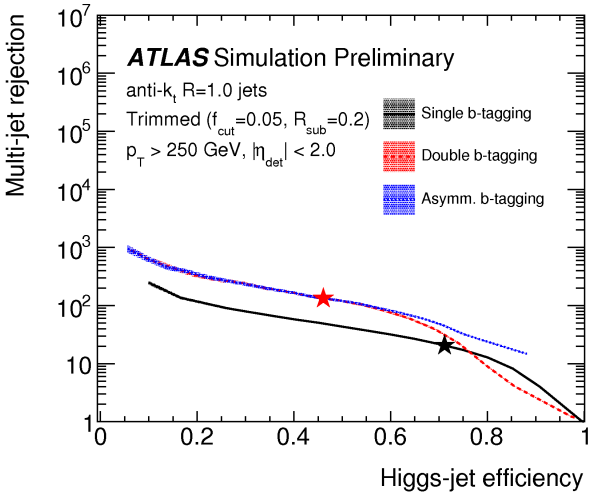
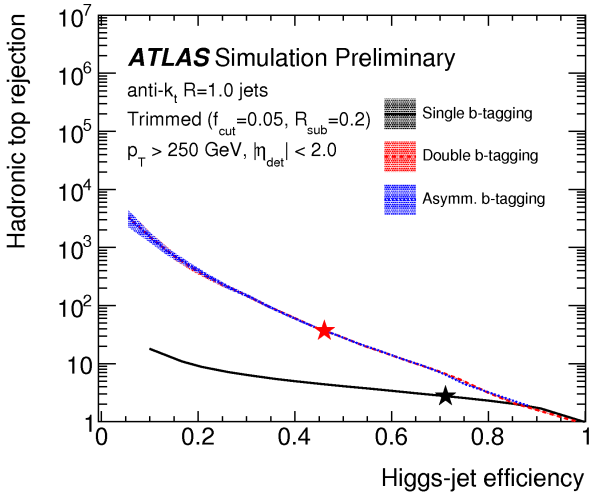
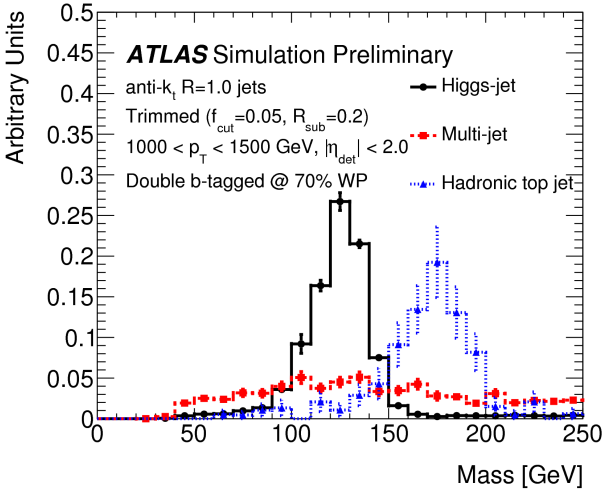
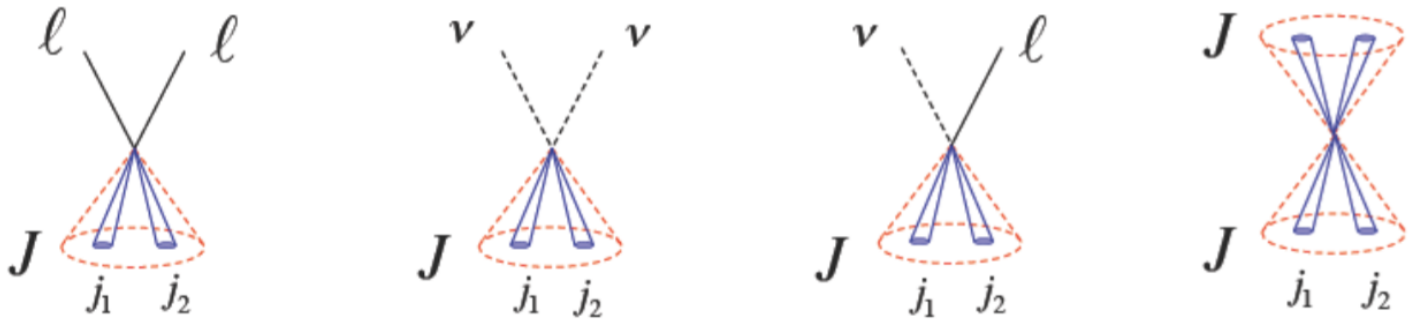






VV Boosted Searches



- *At least one V decays hadronically*
- *Hadronic W and Z signal regions partially overlap*
- *Different VV final states are orthogonal*
- *Interpretations: HVT, RS G*, large/narrow width scalar resonances*

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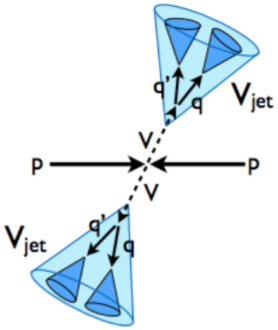
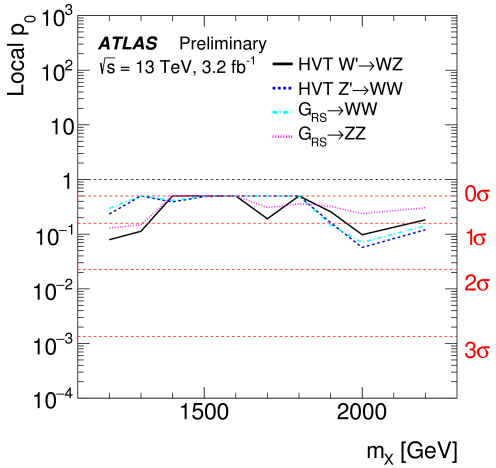
VV→ JJ Searches



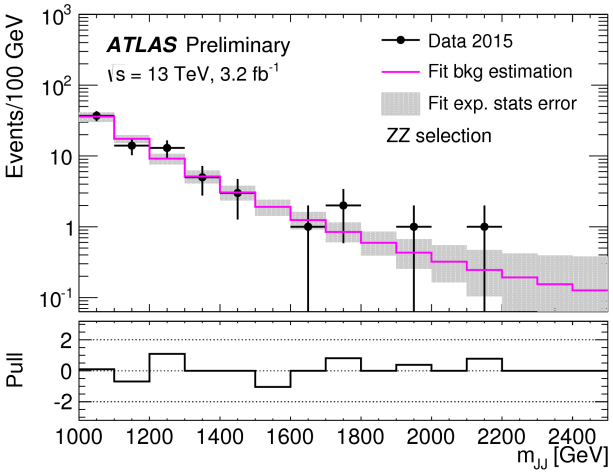
- Two boson tagged large-R jets with p_T > 450 and 200 GeV
- Lepton and E_T^{miss} vetoes are applied
- $|y_1-y_2| < 1.2$ & $(p_T^1-p_T^2)/(p_T^1+p_T^2) < 0.15$
- Number of tracks < 30 → suppress QCD
- Three partially overlapping signal regions WZ, ZZ, WW
- Multi-jet background is dominant and is modeled with:

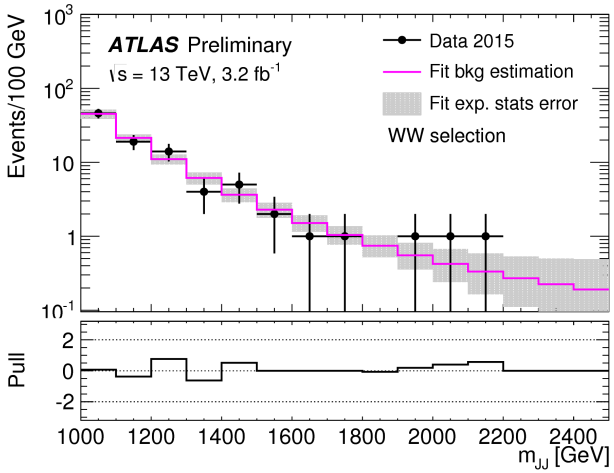
$$\frac{dn}{dx} = p_1(1-x)^{p_2+\xi p_3}x^{p_3} \qquad x = m_{JJ}/\sqrt{s}$$

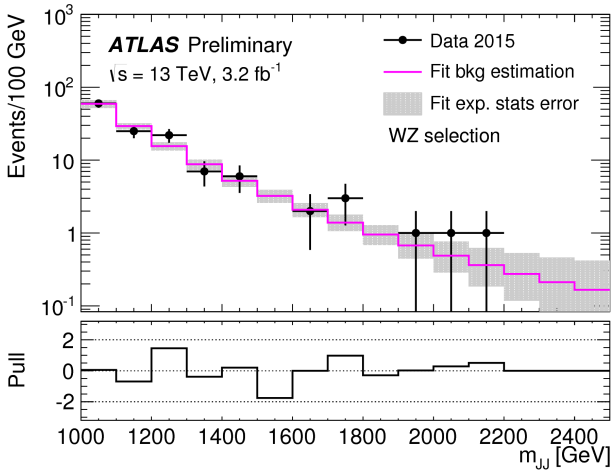


Run I: excess ~2 TeV

Run II: no significant deviation from the background hypothesis

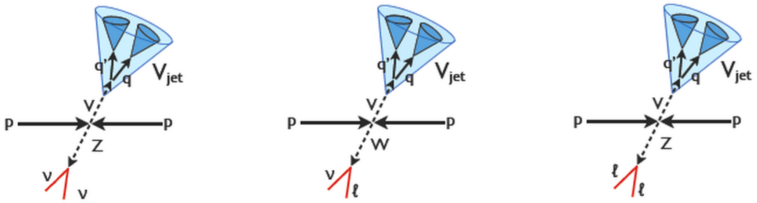






VV→ ννJ/lνJ/llJ Searches

- **One boson tagged large-R jet with p_T > 200 GeV**



WZ/ZZ → ννJ
E_T^{miss}>250GeV
Bkg: V+jets, ttbar, Dibosons

b-jet veto
$\Delta\varphi$ (E_T^{miss},J) < 0.6

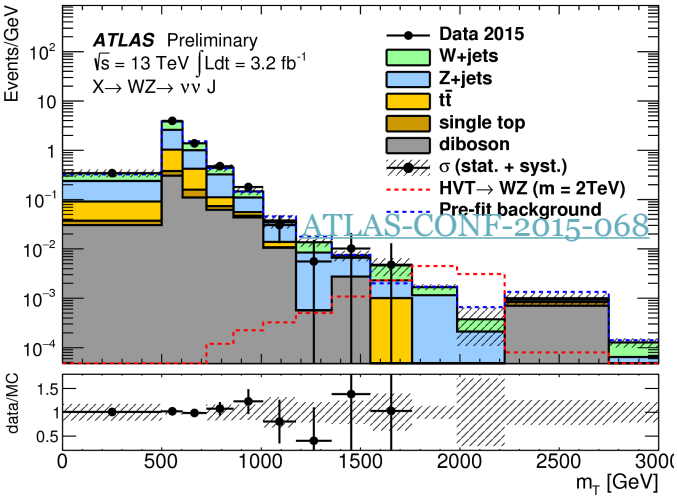
WW/WZ → lνJ
1 lepton + E_T^{miss} > 100 GeV
Bkg: W+jets, ttbar, Dibosons

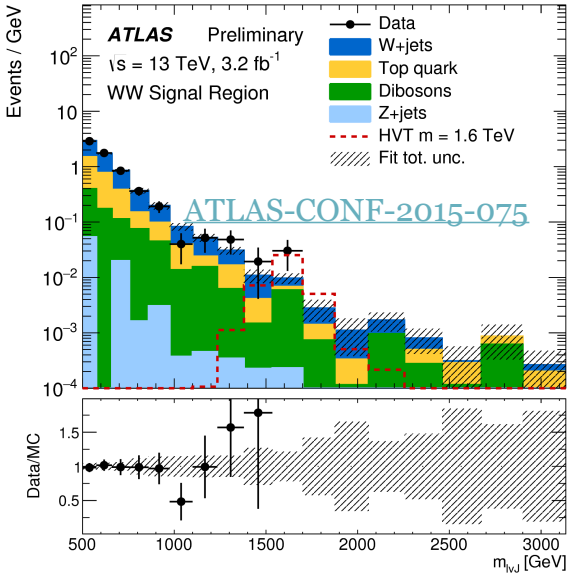
b-jet veto
$p_T(l\nu/J)/m_{l\nu j}$ > 0.4

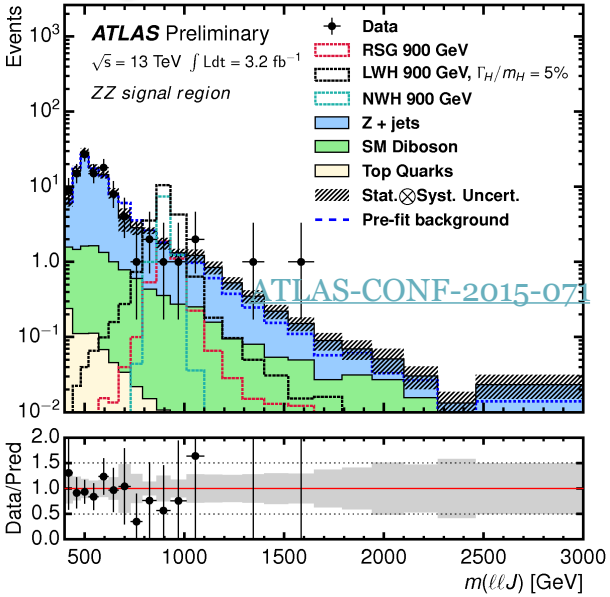
ZW/ZZ → llJ
2 leptons with $m_{ll} \approx m_Z$
Bkg: Z+jets, dibosons

$p_T(ll/J)/m_{llj}$ > 0.4

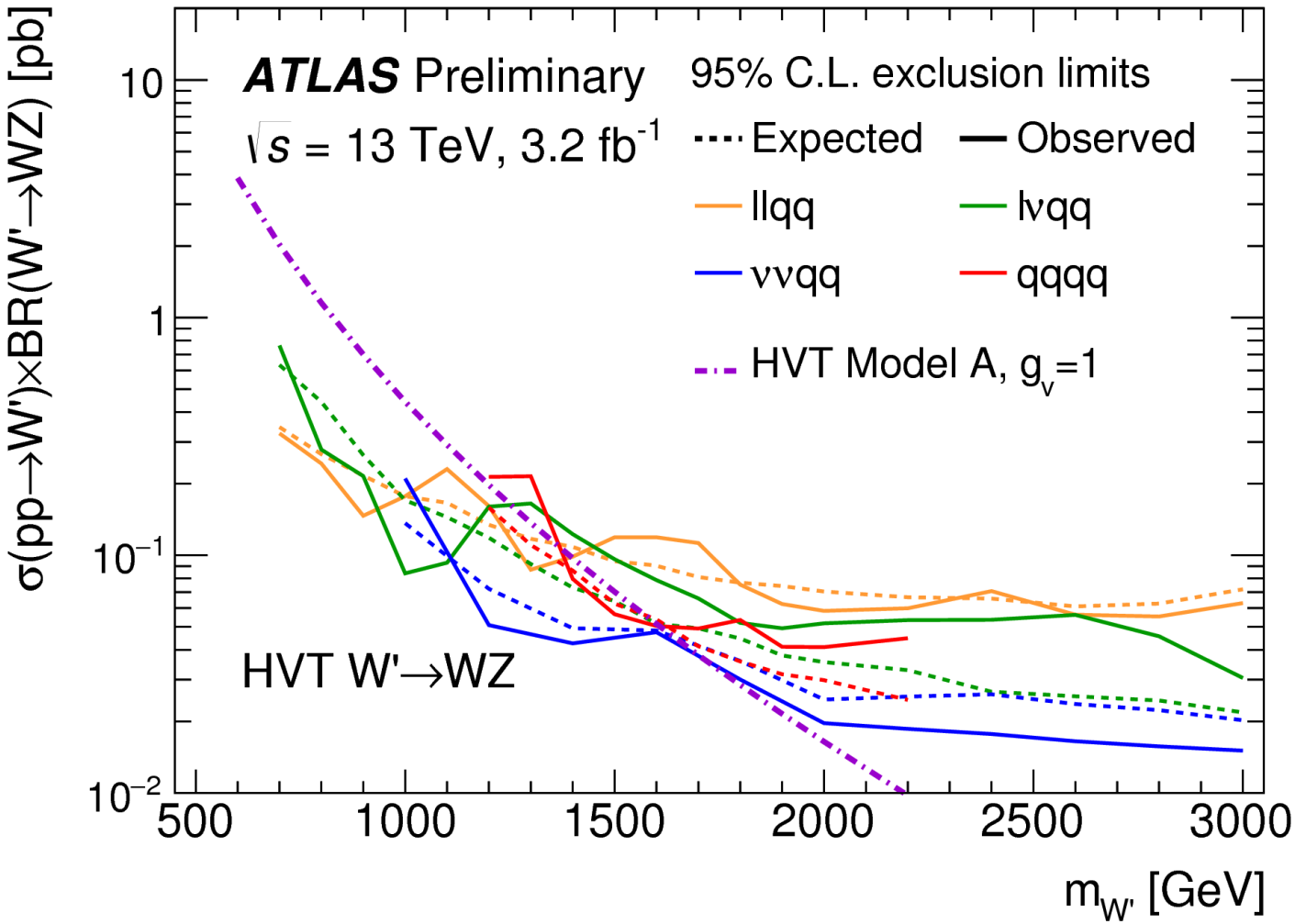
- Background measurement: V+jets J mass sidebands, ttbar inverted b-veto → Included in the final fit







Limits on VV Boosted Resonances



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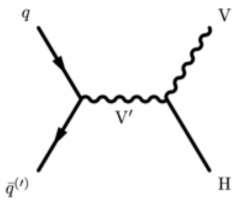
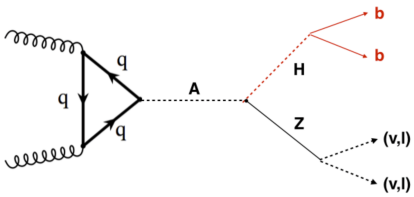
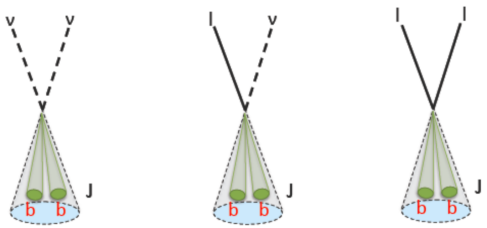
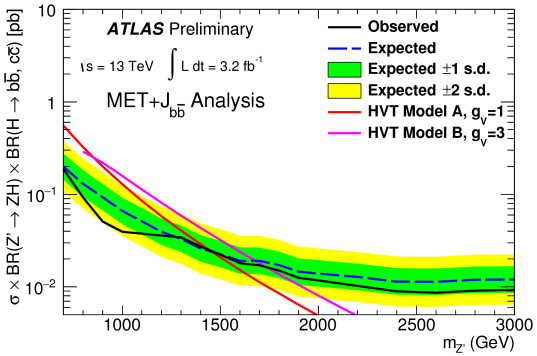


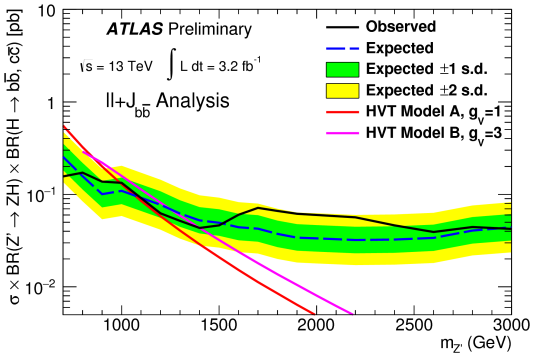
Vh Searches

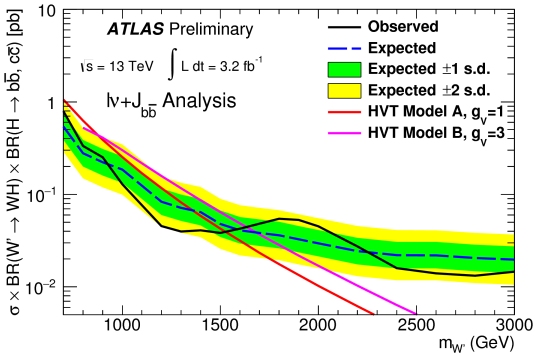


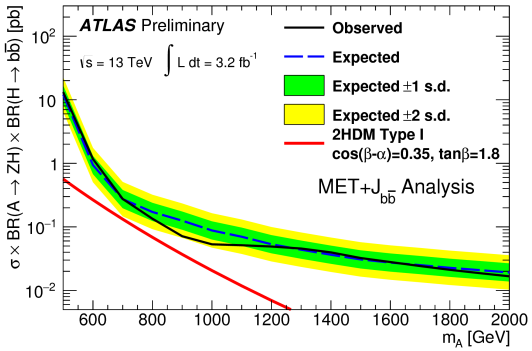
- **V → ll/lν/νν and h → bb**
- Boosted topology very similar to the boosted VV, different large-R jet tagging and 75 < m_J < 145 GeV
- 1 or 2 b-tag categories
- <u>Interpretations</u>: HVT and A → Zh

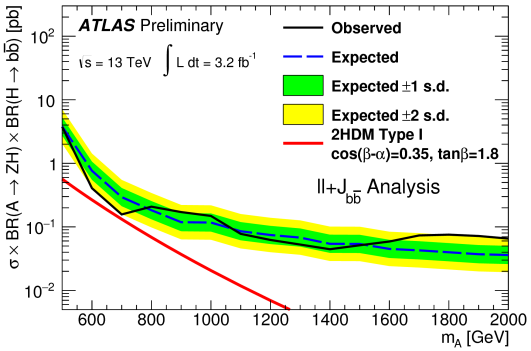












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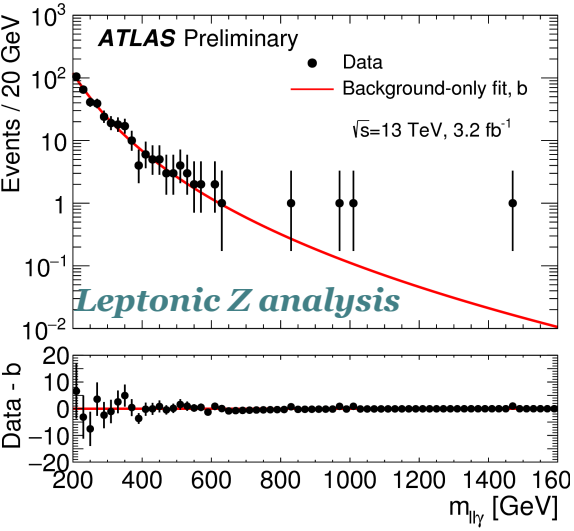
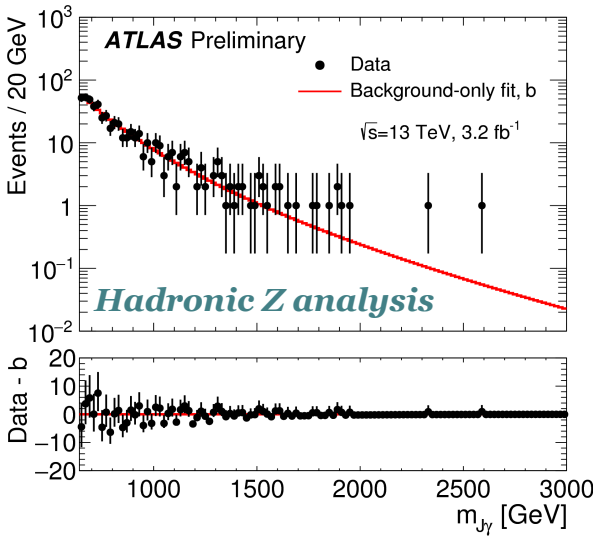
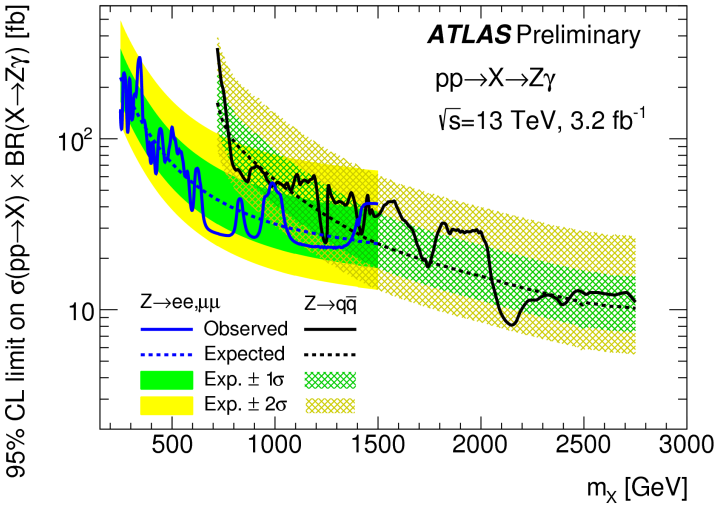
$X^0 \rightarrow Z\gamma$ Searches

- $Z \rightarrow e^-e^+/\mu^-\mu^+/J$
- The boosted regime is studied $p_T(\gamma) > 250$ GeV
- Main backgrounds:
  - Leptonic Z analysis: non-resonant Z+γ, Z+jet (jet misidentified as γ)
  - Hadronic Z analysis: γ+jet, multijet, V+jet
- The background mass distribution is parametrized with: $f_{bkg}(m_{inv}) = \mathcal{N}(1-x^k)^{p_1+\xi p_2} x^{p_2}$, $x = m_{inv}/\sqrt{s}$
  k = 1/3 for leptonic decays and = 1 for hadronic







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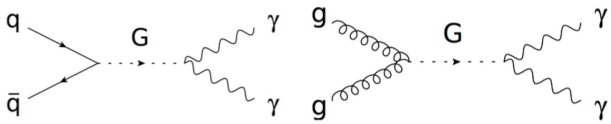
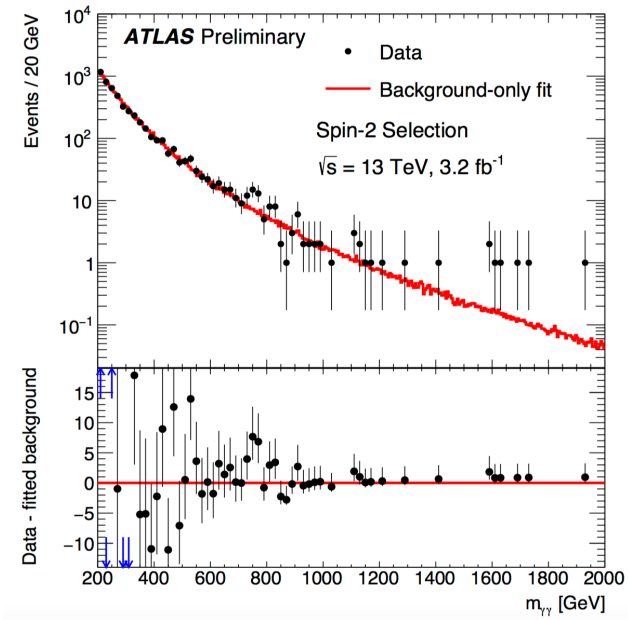
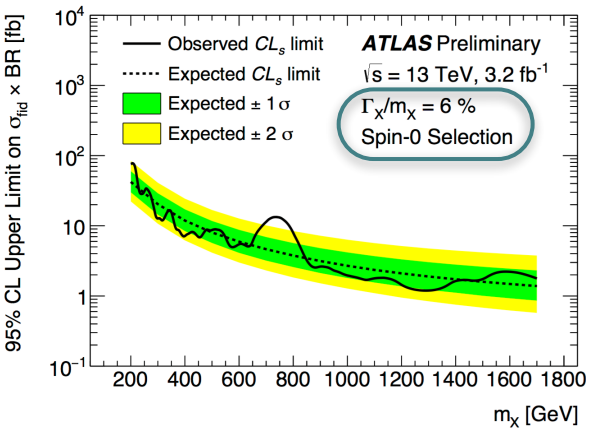
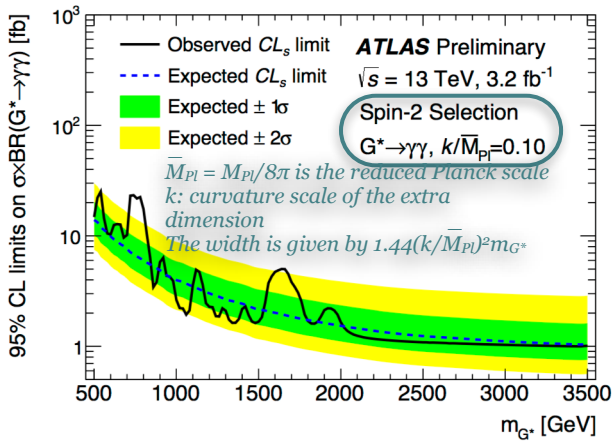
γγ Searches



- **Di-photon resonances, spin 0 or 2, $m_{\gamma\gamma}$ > 200 GeV**
- Irreducible background: *γγ continuum*
- Reducible backgrounds: *γ+jet, jet+jet*
- Spin 0: $E_T^{\gamma 1} / m_{\gamma\gamma} > 0.4$ & $E_T^{\gamma 2} / m_{\gamma\gamma} > 0.3$, Spin 2: $E_T^{\gamma 1,2} > 55$ GeV
- Background: Sidebands functional form (spin 0), template (spin 2)
- Interpretation: Narrow/large width Higgs, RS Graviton







Largest deviation ~ 750 GeV
Global significance:
- Spin 0: 2.0 σ
- Spin 2: 1.8 σ

8 TeV (re-analyzed) data compatibility:
- Spin 0: 1.2 σ (gg) – 2.1 σ (qq)
- Spin 2: 2.7 σ (gg) – 3.3 σ (qq)

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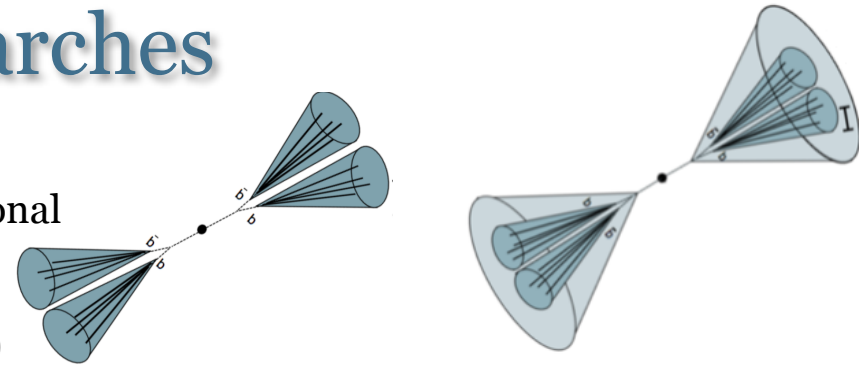
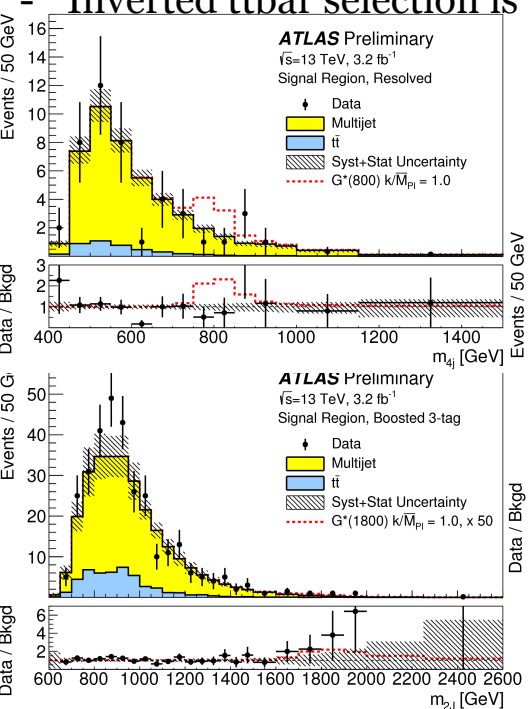
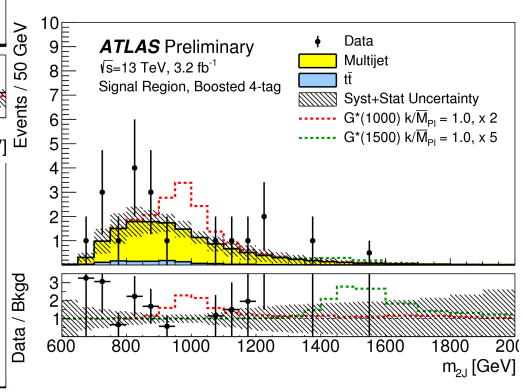
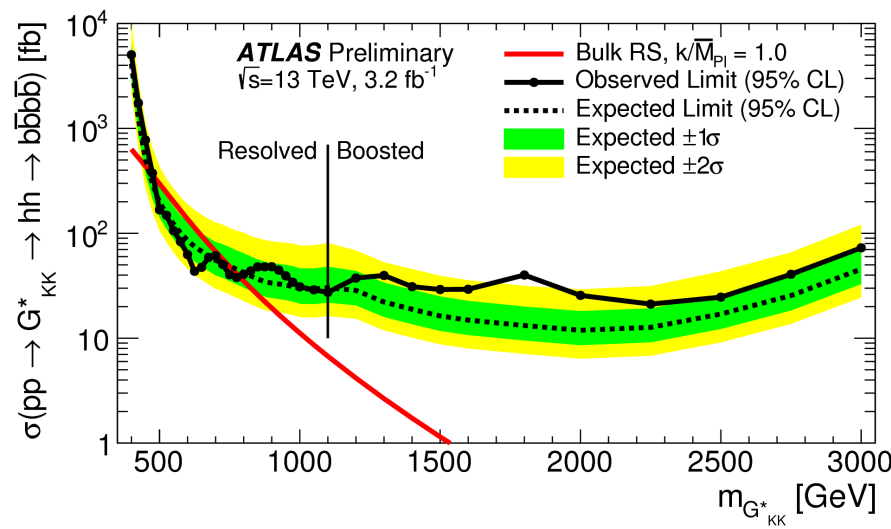
hh→4b Searches



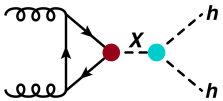
- **Boosted or Resolved**
- $m_{2b} \approx mH$, 3 or 4 b-tagged jets, reject events with additional jets forming objects with $m \approx m_W$ or m_t
- Background composition: multijet (~90%), ttbar (~10%)
- 2-tagged weighted events (kinematic difference due to b-tagging efficiency vs p_T and η) are used for the multijet modeling
- Inverted ttbar selection is used to extract the ttbar normalization, the shape is taken from the MC

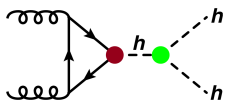




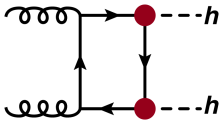


- Interpretations: Graviton and scalar resonance





hh→bbγγ Searches



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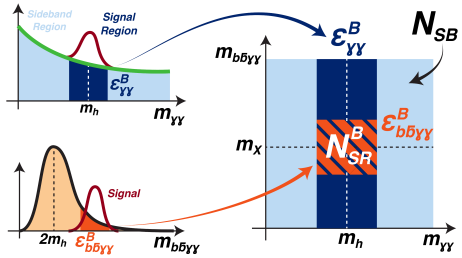
- **105 < $m_{\gamma\gamma}$ < 160 GeV and 95 < m_{bb} <135 GeV (exactly two b-tagged jets)**

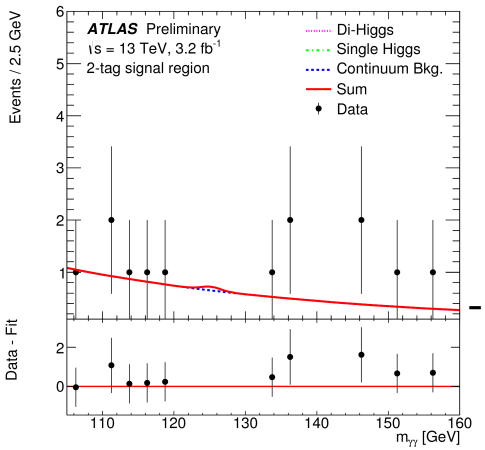
- Resonant Search: counting approach

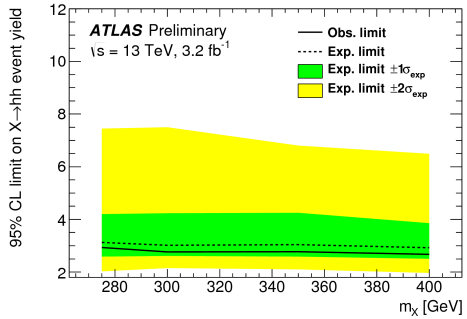


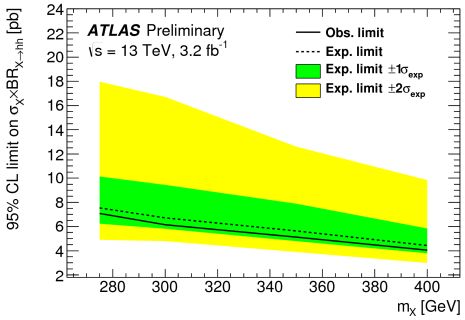
- Non-resonant search:
  - *a fit to the $m_{\gamma\gamma}$ distribution is performed simultaneously in the 0b-tag and 2b-tag regions*
  - *The shape is extracted from an exponential fit to the $m_{\gamma\gamma}$ sidebands*

- The efficiency of non-resonantly produced hh to pass these selection is 10% > Efficiency of the resonantly produced hh 5%-8%

- Non-resonant decay products tend to have higher p_T and are more likely to pass the selection







- **Cross section upper limits at 95% confidence level**:
  - Non-resonant: *3.9 pb (expected 5.4 pb)*
  - Narrow resonance: *7.0 - 4.0 pb (expected 7.5 - 4.4 pb) @ 275–400 GeV*

Summary

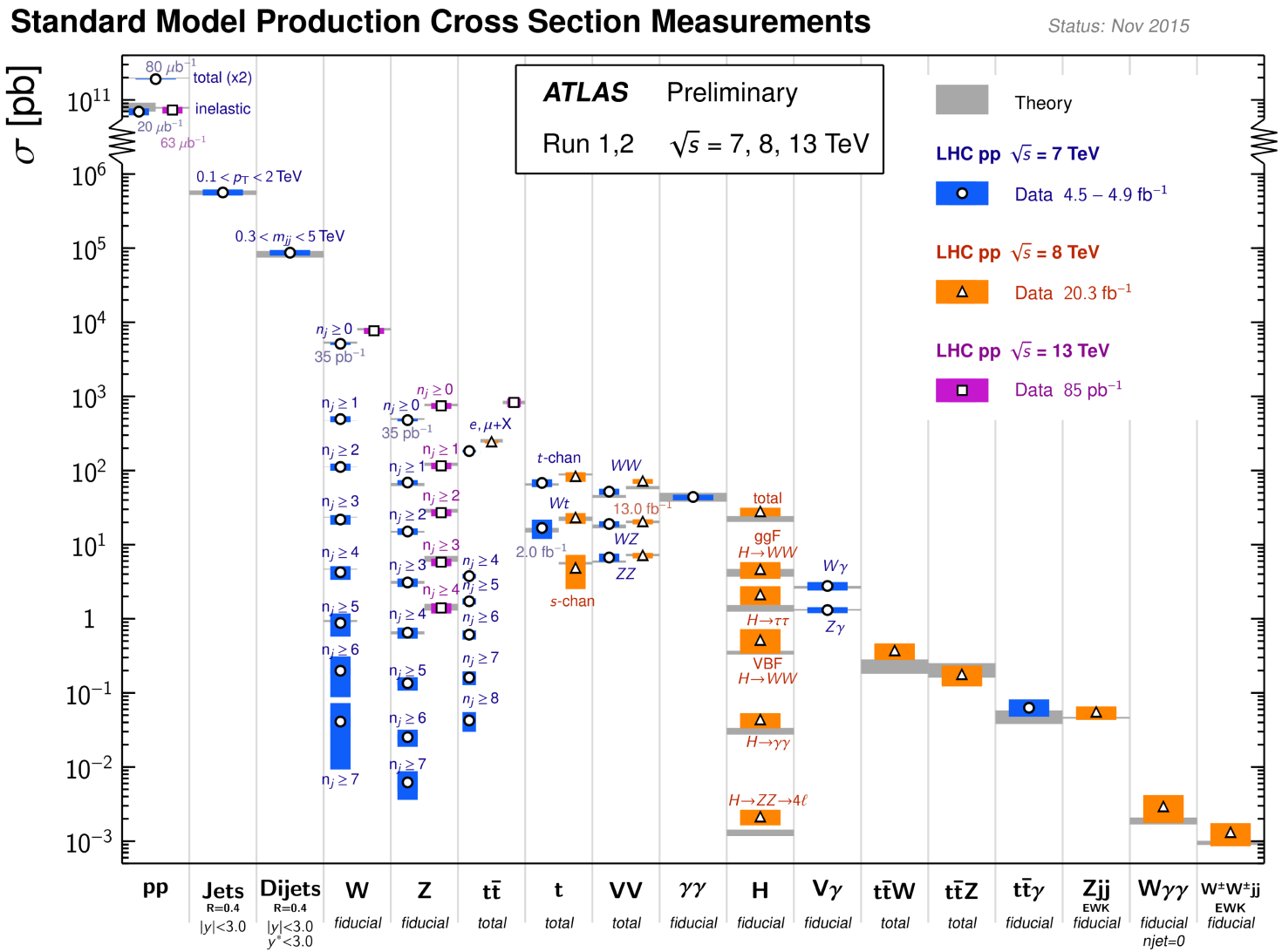
- Latest ATLAS Run II results of searches with bosons presented
- One of the most direct ways to discover new physics at the TeV scale
- Boosted object tagging is an important key to probe high mass new physics
- Improved limits set
- More data are needed to (dis-)prove various small/modest excesses and models
- More data is coming soon

Thank you for your attention!

Back - up Slides

SM Summary

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



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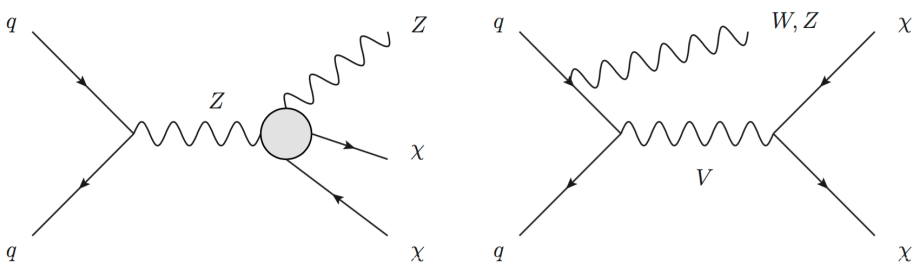
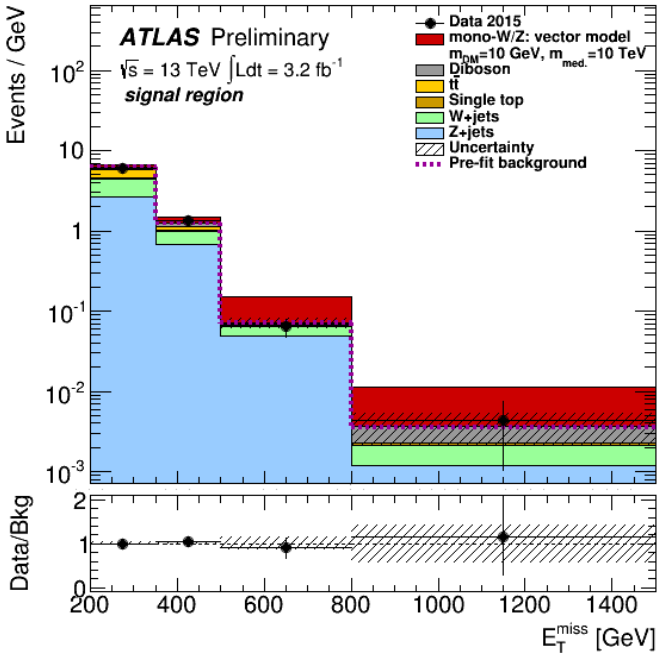
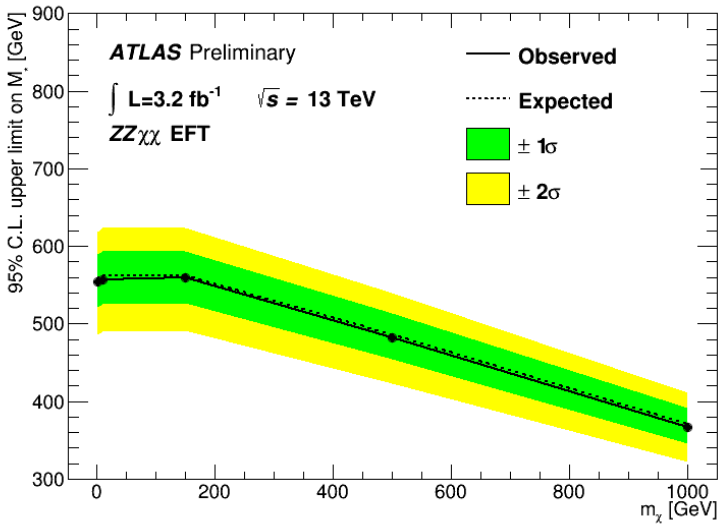
Mono-V Searches

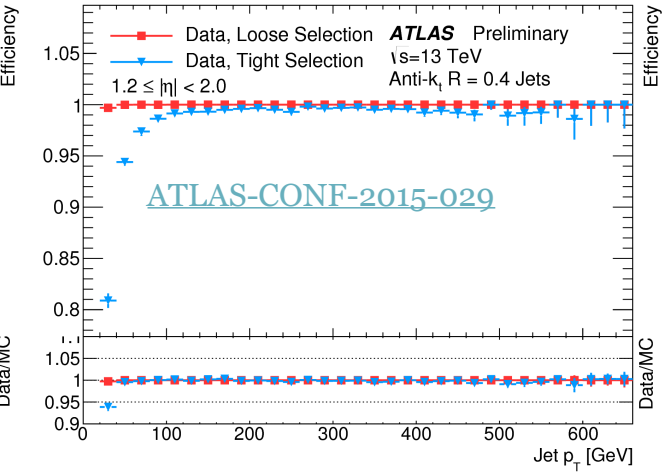
- Dark matter search in association with a hadronically decaying W/Z boson
- Very similar final state to the VV → ννJ
- E_T^{miss} is the final discriminant
- Results are interpreted in the Effective Field Theory (EFT) and simplified model frameworks



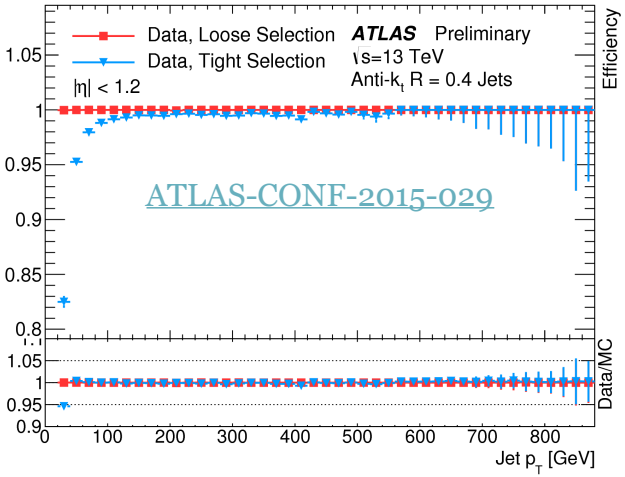




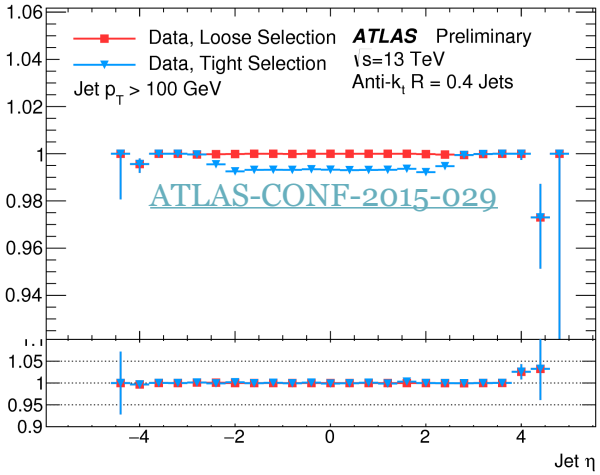
Small-R Jets



ATLAS-CONF-2015-029



ATLAS-CONF-2015-029



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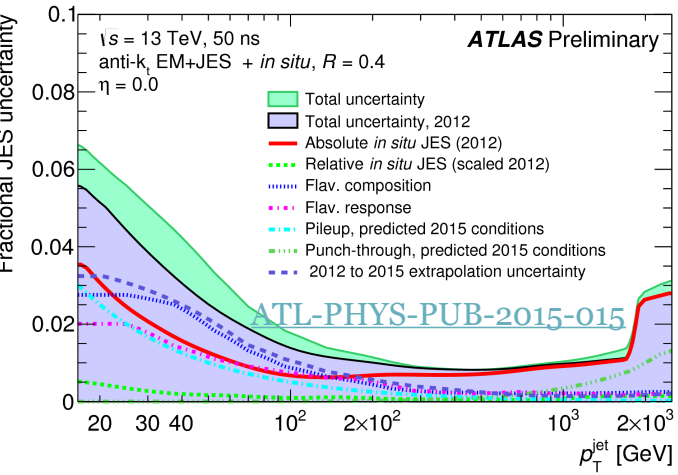
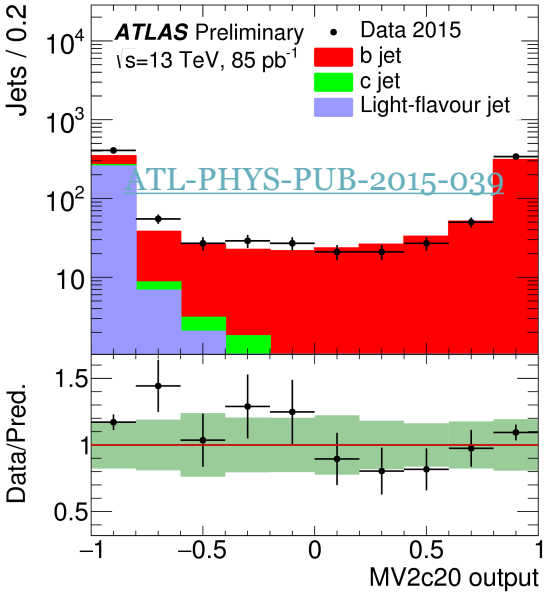


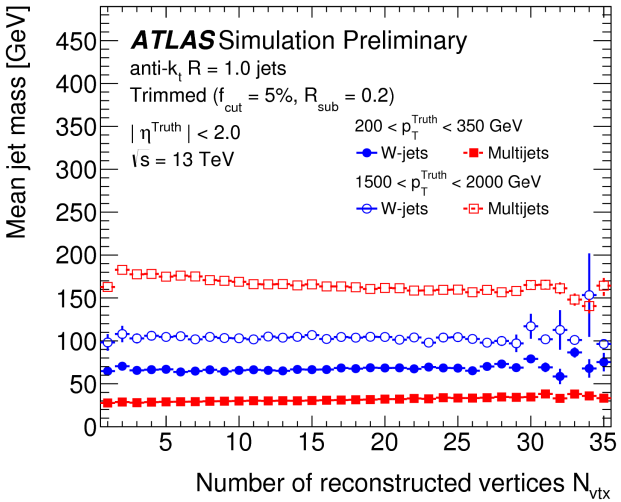
ATL-PHYS-PUB-2015-015

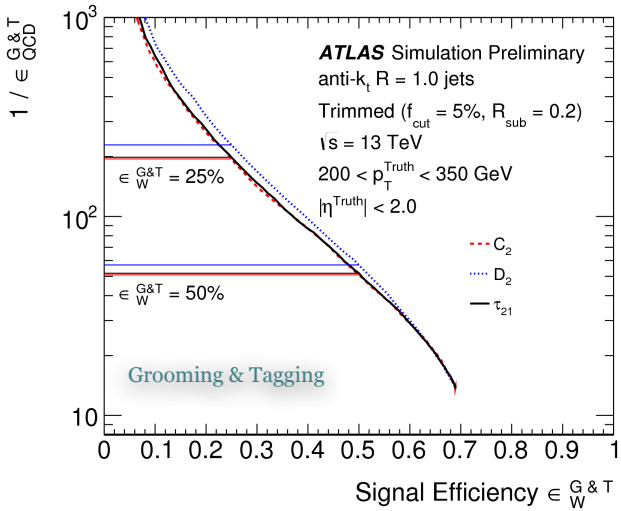


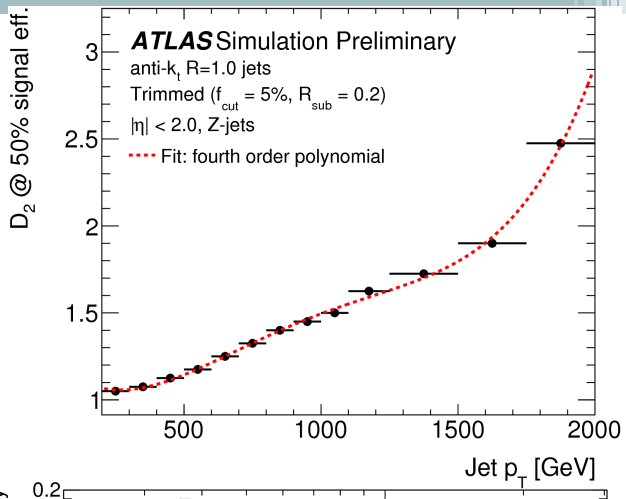
ATL-PHYS-PUB-2015-039

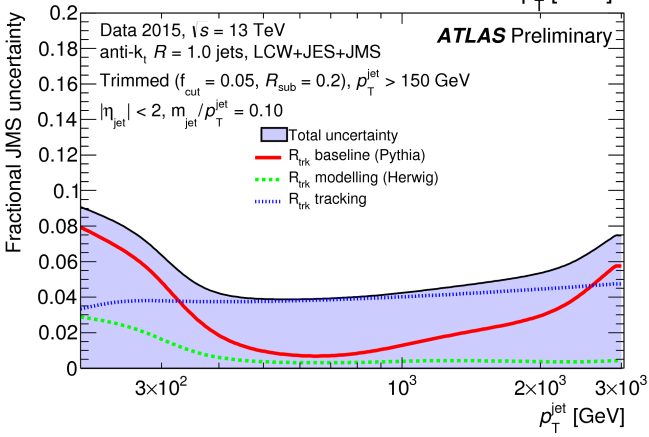
ATL-PHYS-PUB-2015-033

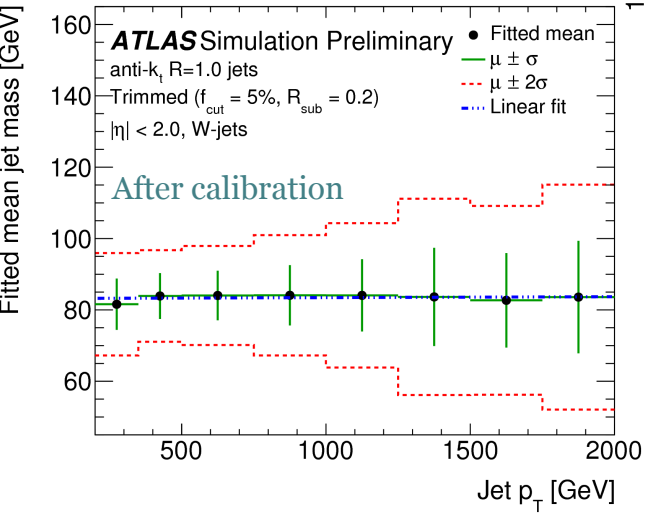
Large-R Jets

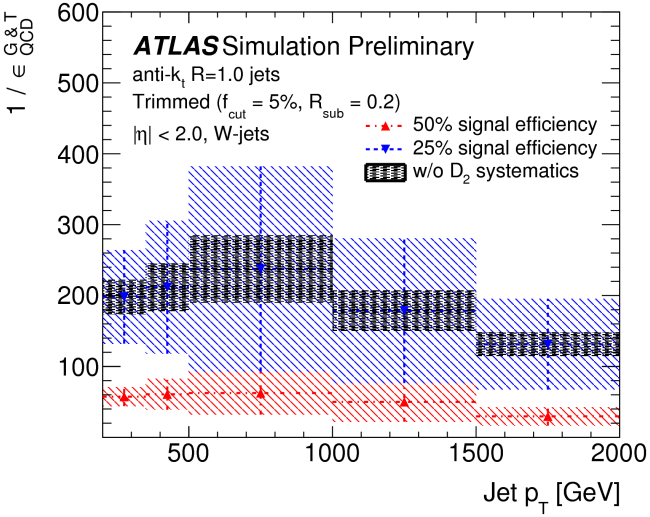


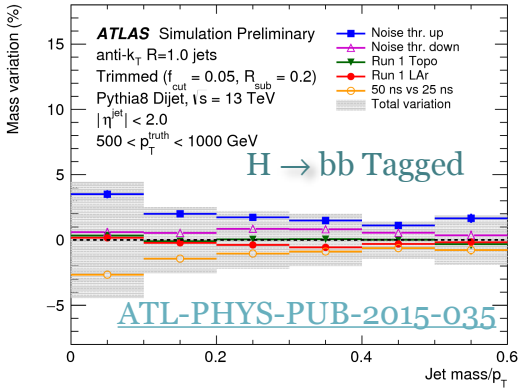






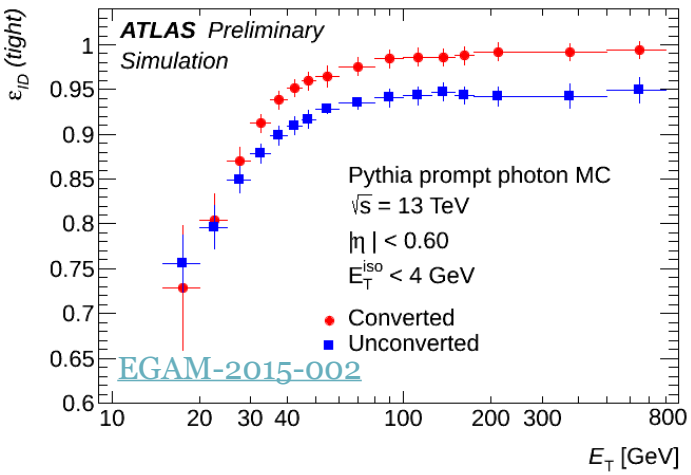


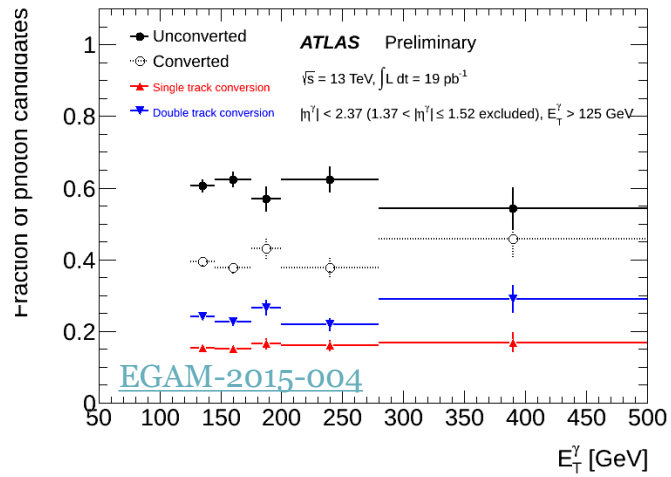


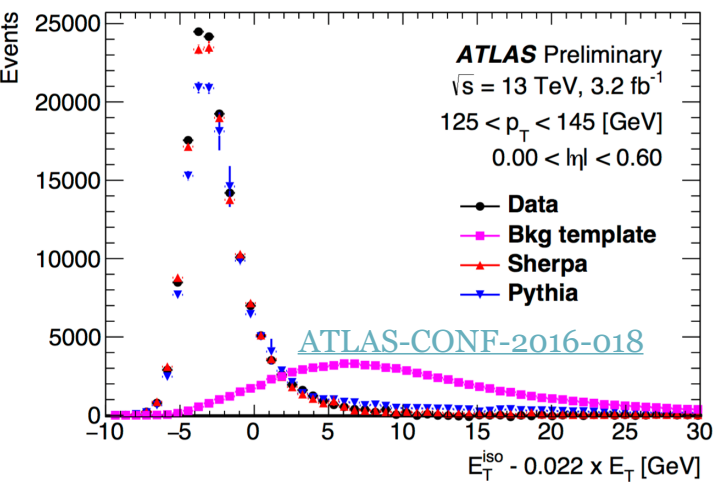


ATL-PHYS-PUB-2015-035

Photon ID/Isolation







Identification:
- 85% E_T~50 GeV
- Uncertainty ±1% - ±5% (η dependent)

Isolation:
- Calorimeter ($\Delta R = 0.4$) $E_T^{iso} < 0.022\ E_T^{\gamma} + 2.45$ GeV
- Track ($\Delta R = 0.2$) $p_T^{iso} < 0.05\ E_T^{\gamma}$

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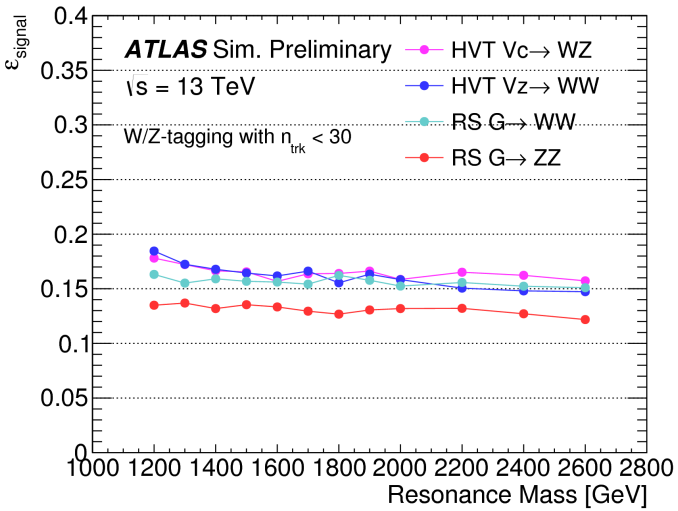
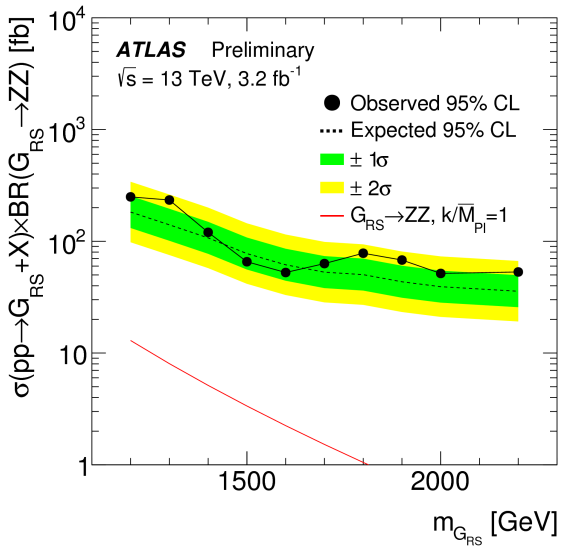
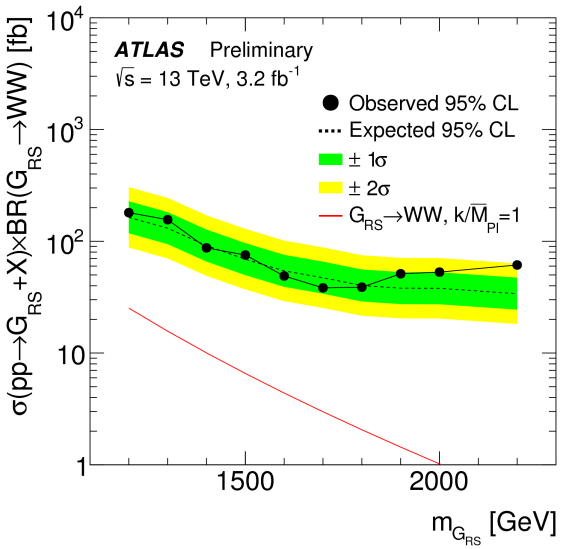
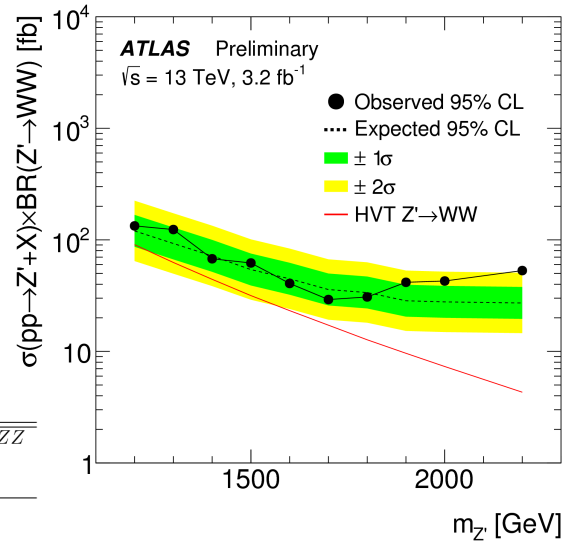
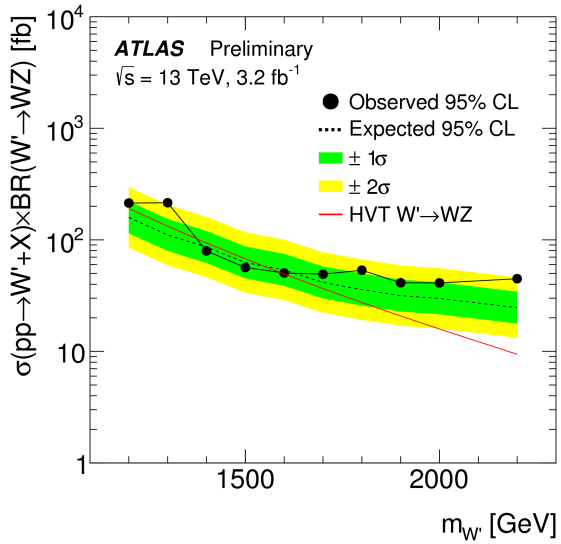
VV→ JJ











m [TeV]	Γ_{HVT} [GeV]	$W' \to WZ$ $\sigma \times$BR [fb]	$Z' \to WW$ $\sigma \times$BR [fb]	$\Gamma_{G_{RS}}$ [GeV]	$G_{RS} \to WW$ $\sigma \times$BR [fb]	$G_{RS} \to ZZ$ $\sigma \times$BR [fb]
1.3	33.3	62.7	28.7	76	7.2	3.9
1.6	40.9	23.3	10.6	96	2.0	1.1
2.0	51.0	7.6	3.35	123	0.47	0.25

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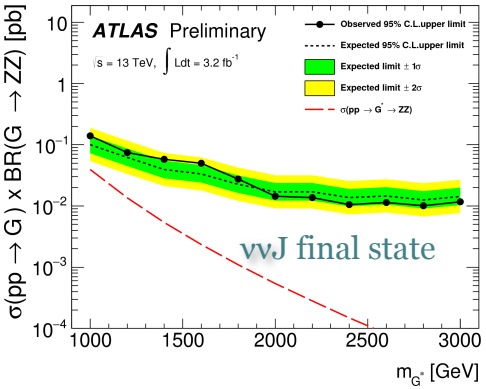
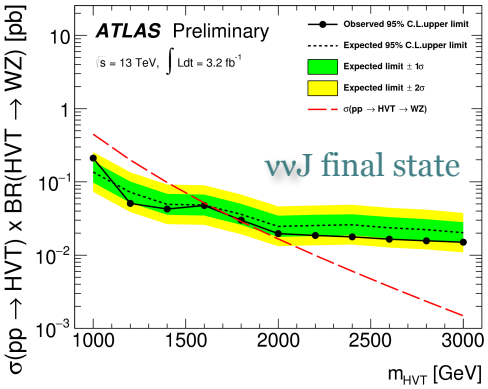
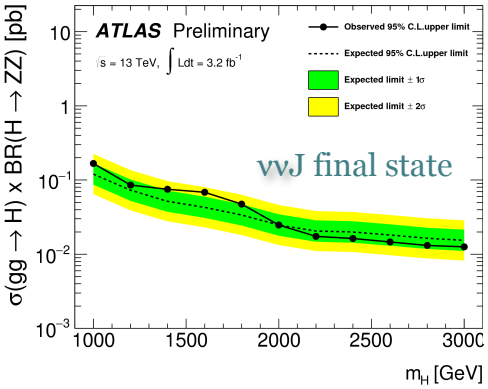
ATLAS-CONF-2015-075

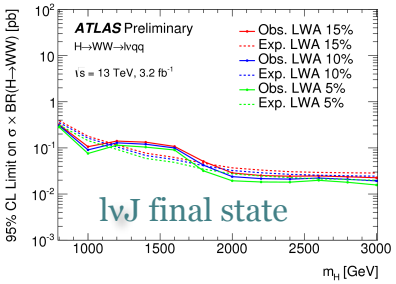
ATLAS-CONF-2015-068

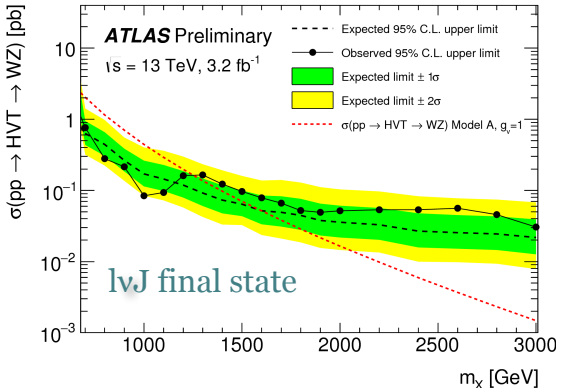
VV

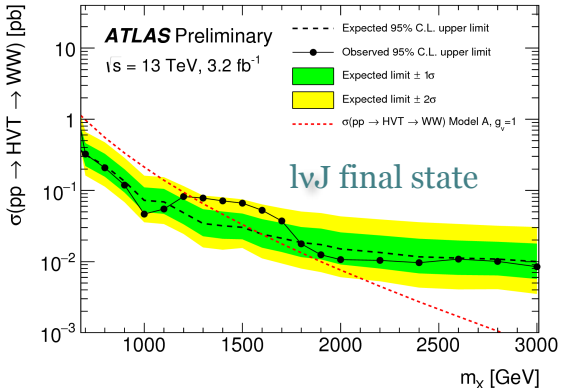


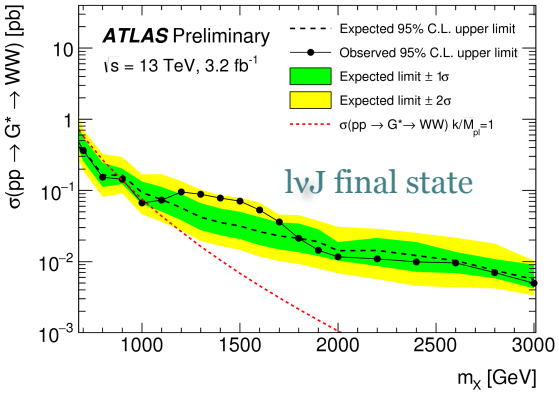


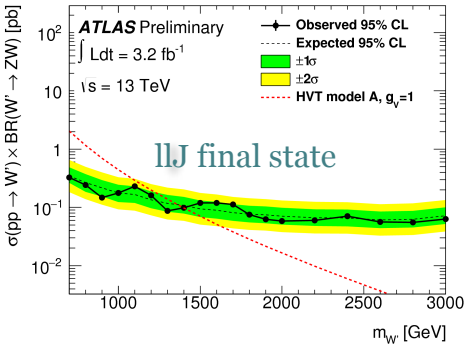


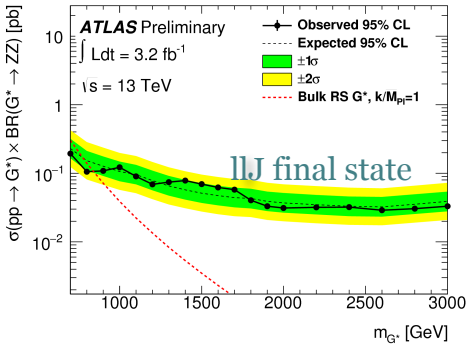


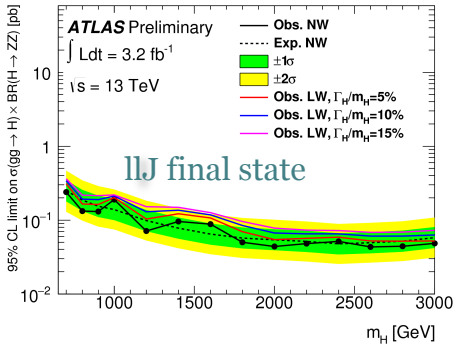




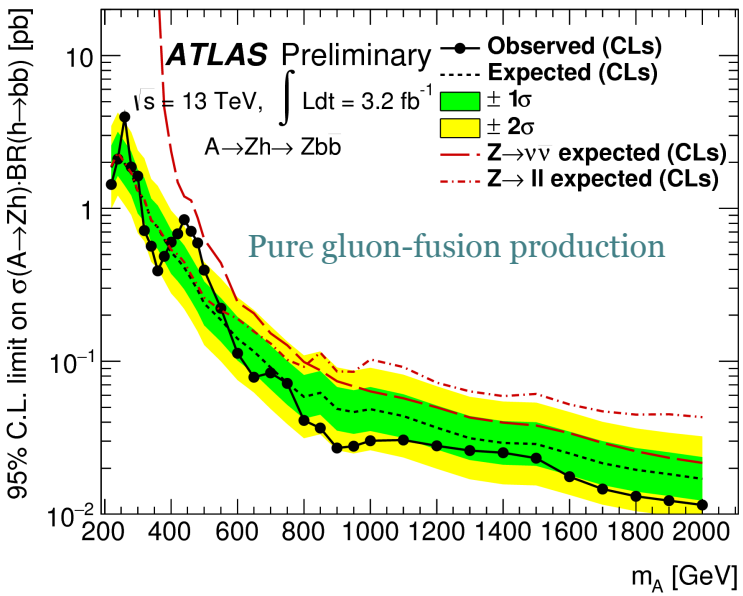


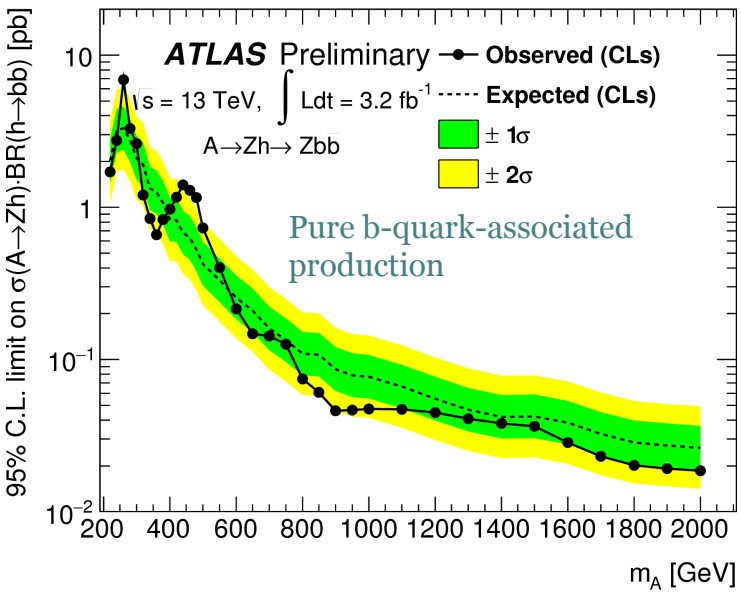






A→Zh (h→bb) Resolved/Merged





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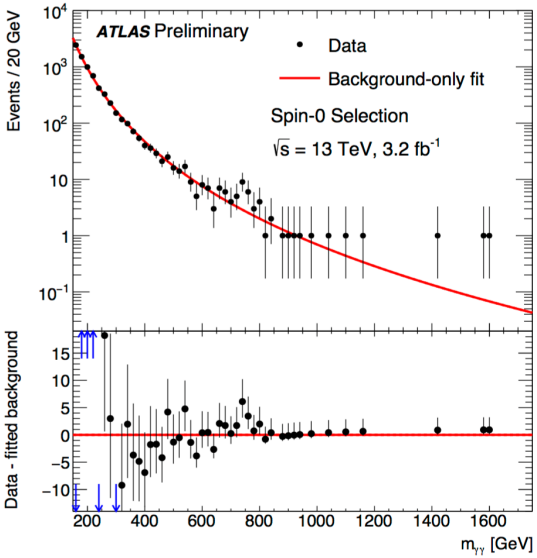
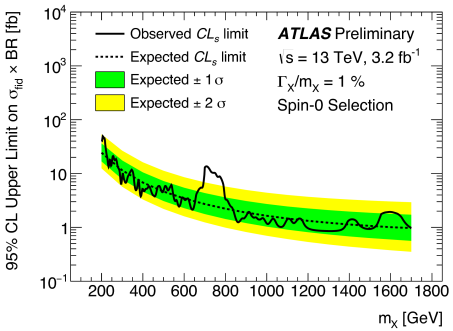
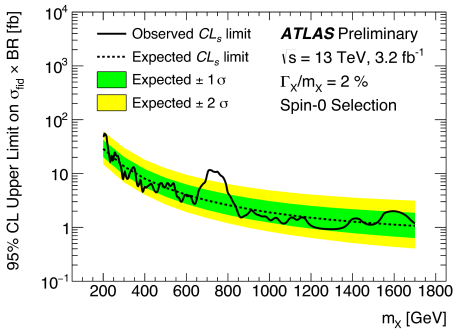
Di-Photon Searches

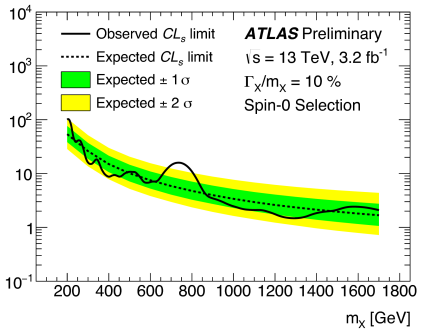
Higgs Width:
- Narrow Higgs = 4 MeV
- Large Width Higgs ≤10% m_X

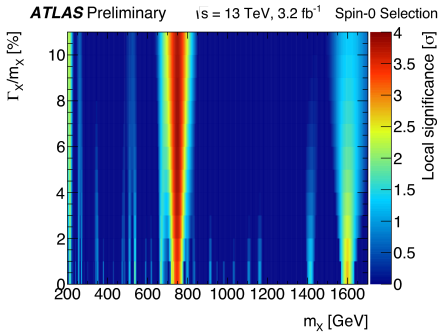
Background Modeling:
- Spin 0 : $f_{(k)}(x;b,\{a_k\}) = N(1-x^{1/3})^b x^{\sum_{j=0}^{k} a_j (\log x)^j}$ $\quad x = \frac{m_{\gamma\gamma}}{\sqrt{s}}$
- Spin 2: template MC (γγ) & data (reducible bkg, inverting tight shower shape criteria)

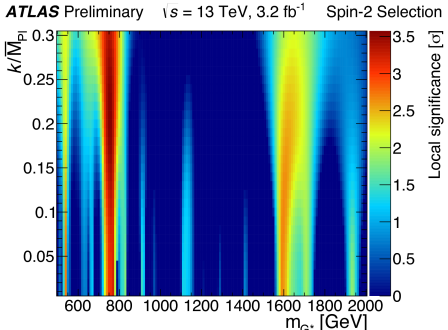


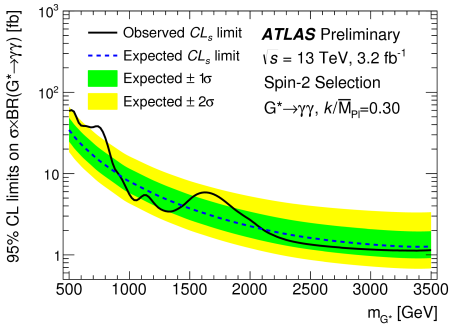


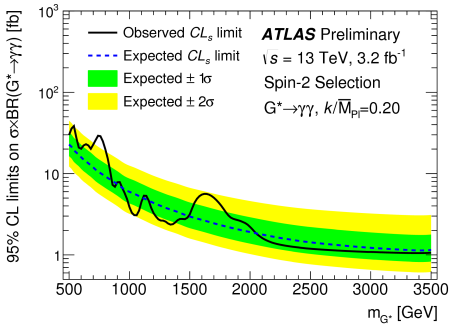


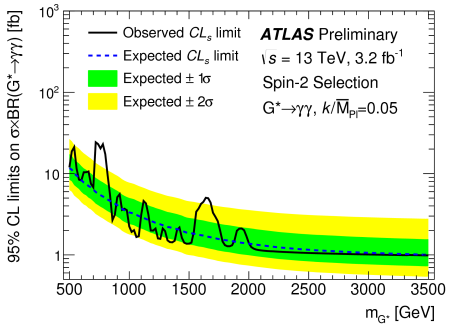












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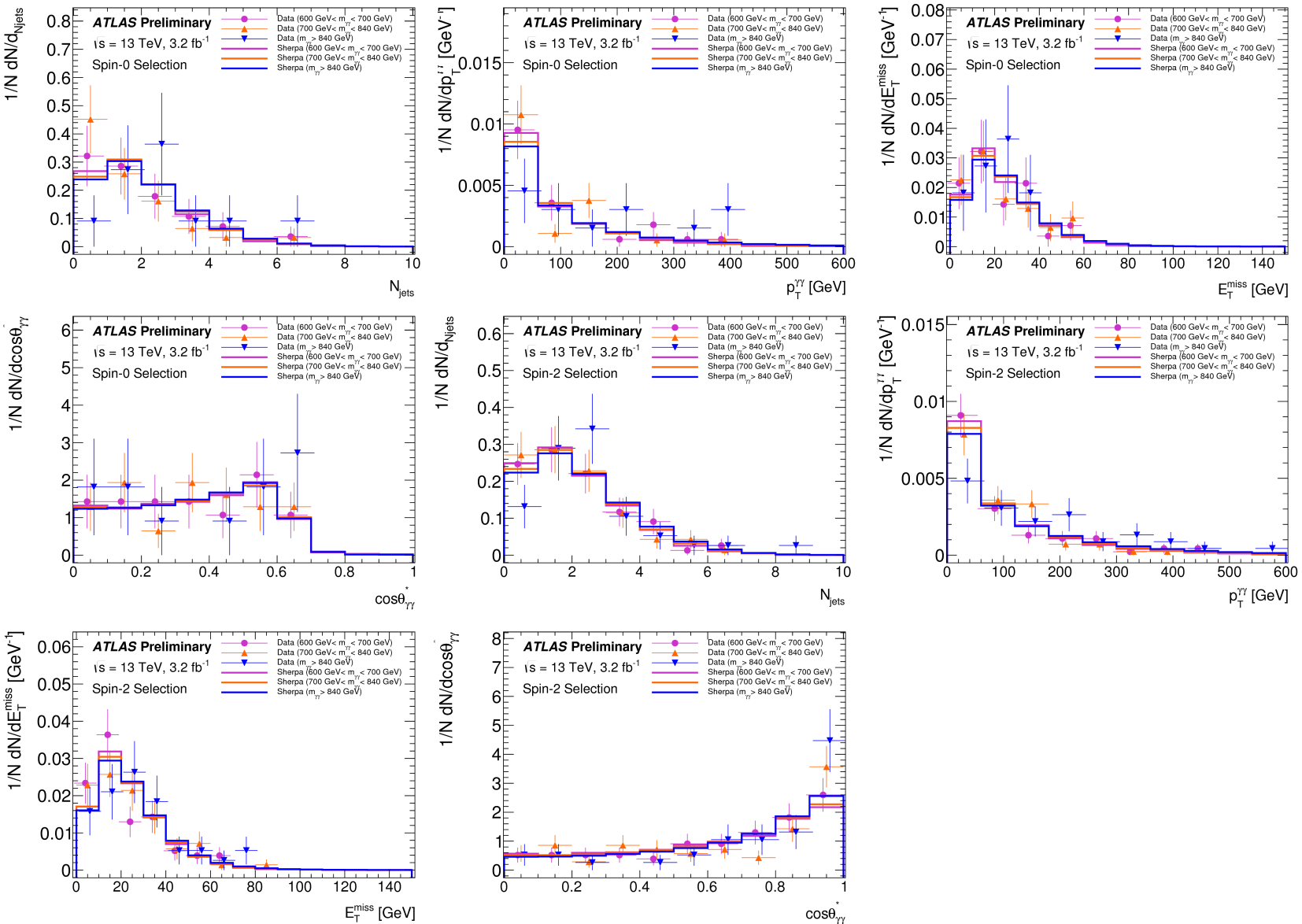
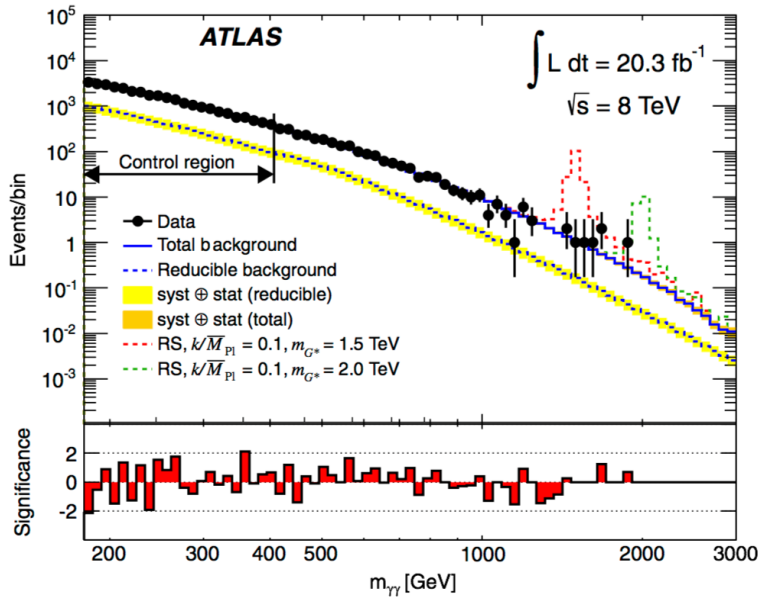
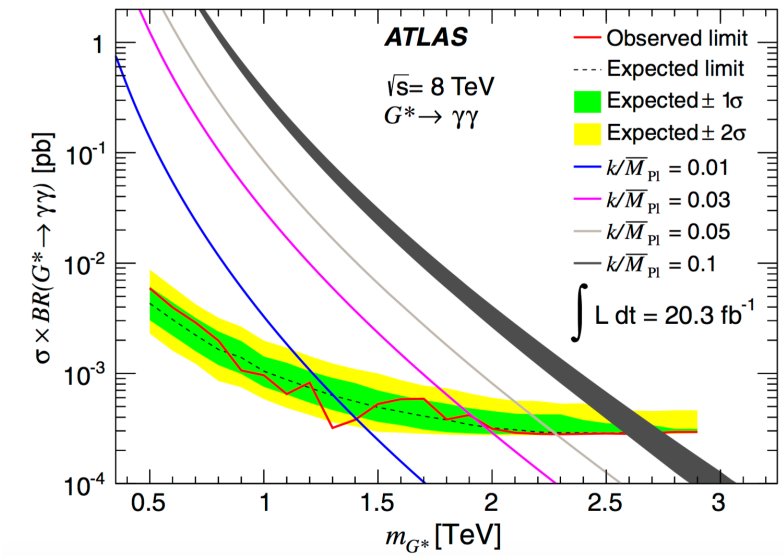
Di-Photon Events Properties



High Mass Di-Photon Run I Search





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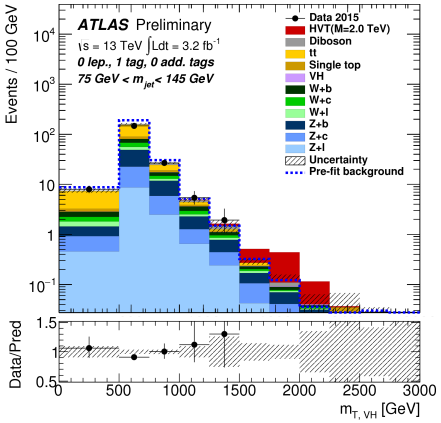
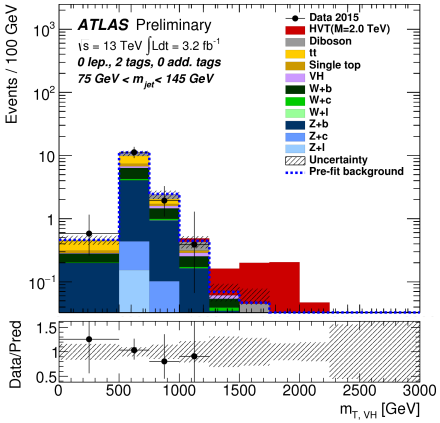
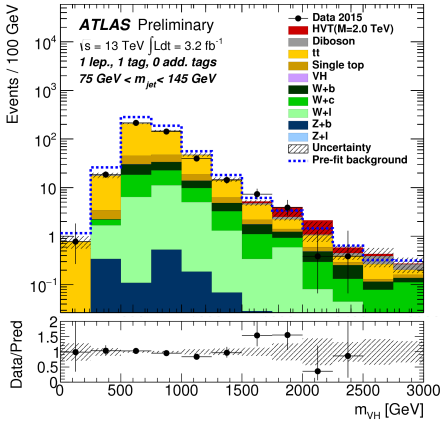
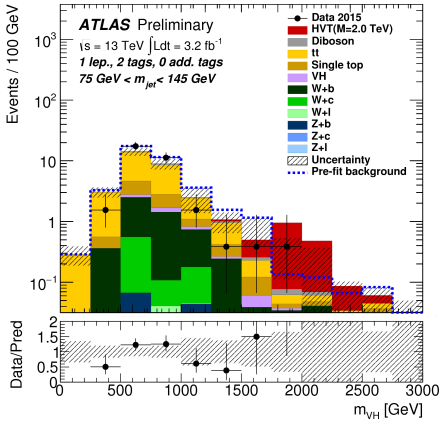
Vh Searches



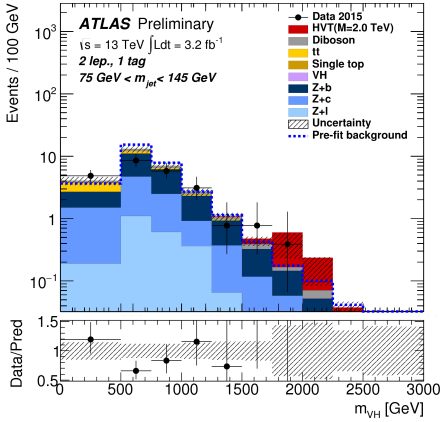


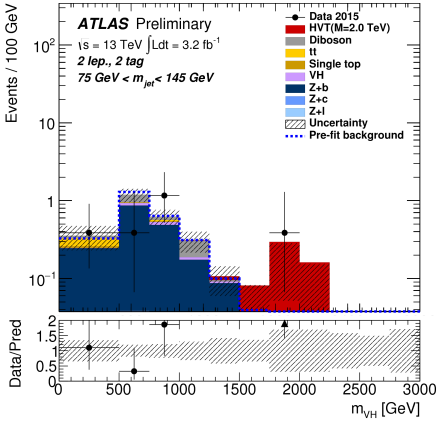
0 lepton





1 lepton





2 leptons

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Vh Searches

- Background:
  - Composition V+jets, ttbar, multijets
  - m_h sidebands: low region dominated by V+Jets, high region by ttbar
  - ttbar background validation:
    - 0 and 1 lepton channels: requiring at least one b-jet not associated to the large-R jet
    - 2 leptons channel: exactly one electron and one muon, at least one b-jet in the large-R jet

Two b-tags			
	$\nu\nu b\bar{b}$	$\ell\nu b\bar{b}$	$\ell\ell b\bar{b}$
$t\bar{t}$	7.8 ± 2.0	51 ± 9	0.41 ± 0.21
single top	2.0 ± 0.6	9.8 ± 2.3	0.05 ± 0.02
$W + b$	7.1 ± 2.0	13 ± 4	–
$W + c$	0.7 ± 0.4	1.9 ± 0.6	–
$W + l$	0.06 ± 0.06	1.62 ± 0.25	–
diboson	3.8 ± 0.7	2.8 ± 0.5	1.1 ± 0.3
VH	1.5 ± 0.6	1.2 ± 0.9	0.33 ± 0.06
$Z + b$	12.5 ± 3.1	0.37 ± 0.15	5.1 ± 1.0
$Z + c$	0.9 ± 0.4	0.04 ± 0.01	0.16 ± 0.08
$Z + l$	0.50 ± 0.35	–	0.02 ± 0.01
backgrounds	36.9 ± 3.4	81 ± 8	7.2 ± 1.1
data	38	85	7
One b-tag			
	$\nu\nu b\bar{b}$	$\ell\nu b\bar{b}$	$\ell\ell b\bar{b}$
$t\bar{t}$	198 ± 16	781 ± 36	8.65 ± 1.6
single top	27 ± 7	92 ± 19	1.00 ± 0.32
$W + b$	42 ± 11	74 ± 18	–
$W + c$	38 ± 13	80 ± 19	–
$W + l$	23 ± 8	1.36 ± 0.15	–
diboson	25 ± 4	24 ± 4	6.0 ± 1.5
VH	1.5 ± 0.6	2.4 ± 1.8	0.25 ± 0.05
$Z + b$	86 ± 20	3.2 ± 2.7	38 ± 5
$Z + c$	47 ± 17	0.00 ± 0.06	20 ± 5
$Z + l$	32 ± 11	0.03 ± 0.06	7.5 ± 2.5
backgrounds	524 ± 17	1120 ± 28	82 ± 7
data	508	1147	75

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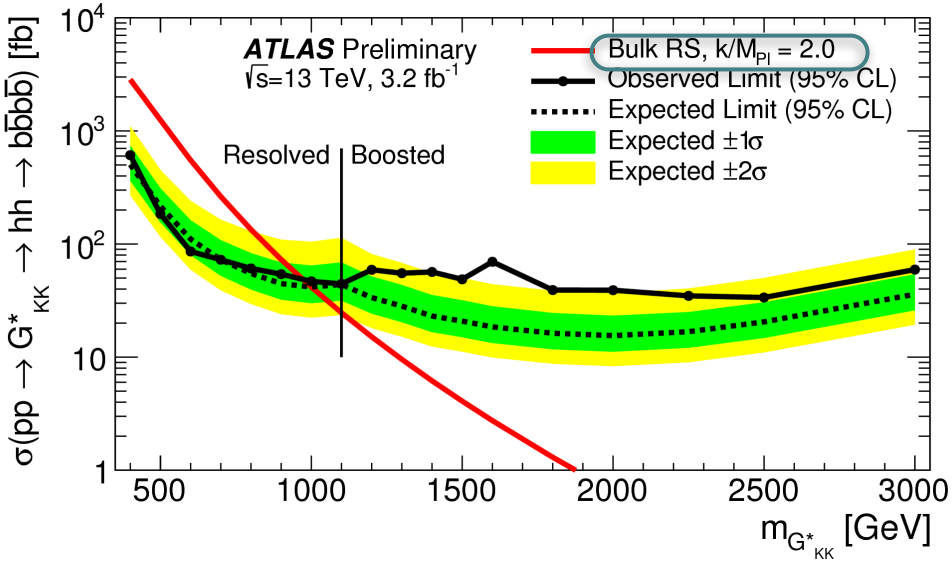
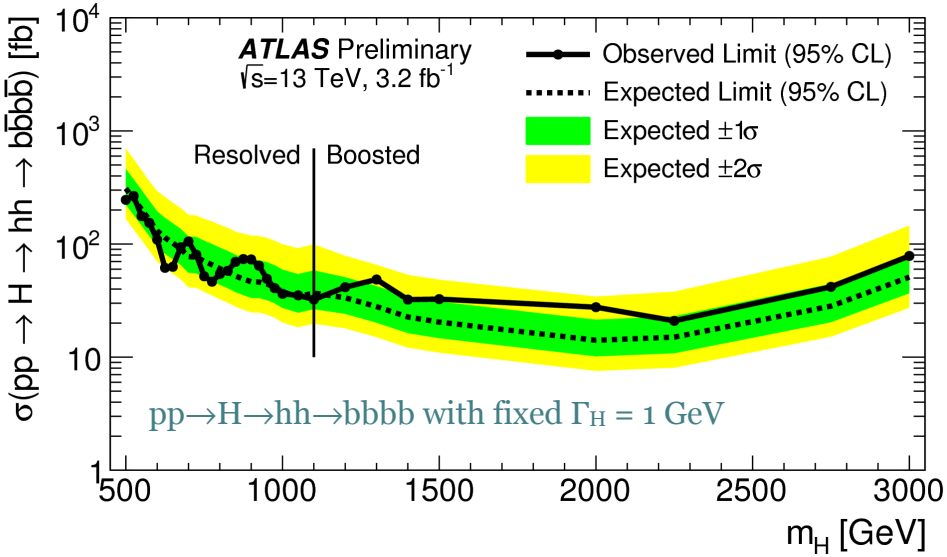
hh→4b Searches





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hh→bbγγ Searches

Resonant search:

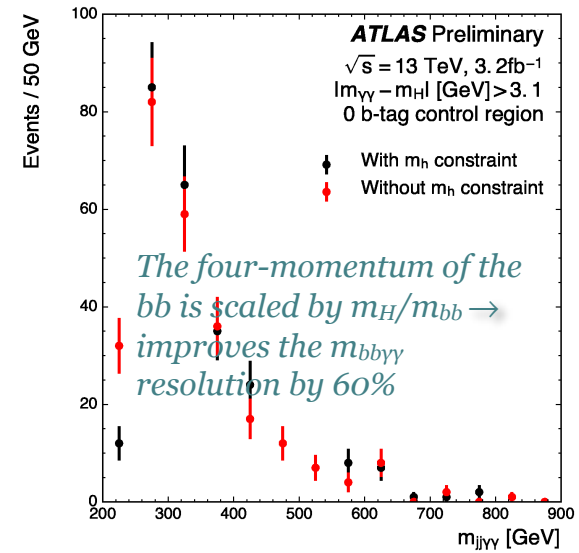
$$N_{SR}^{B} = N_{SB}\frac{\varepsilon_{m_{\gamma\gamma}}^{B}}{1-\varepsilon_{m_{\gamma\gamma}}^{B}}\varepsilon_{m_{b\bar{b}\gamma\gamma}}^{B}$$

- N_{SB} :number of observed events in the $m_{\gamma\gamma}$ sidebands
- $\varepsilon^{B}_{m\gamma\gamma}$ efficiency to pass the $m_{\gamma\gamma}$ cut
- $\varepsilon^{B}_{mbb\gamma\gamma}$ efficiency to pass the $m_{bb\gamma\gamma}$ cut

Contribution from single-h or non-resonant hh:

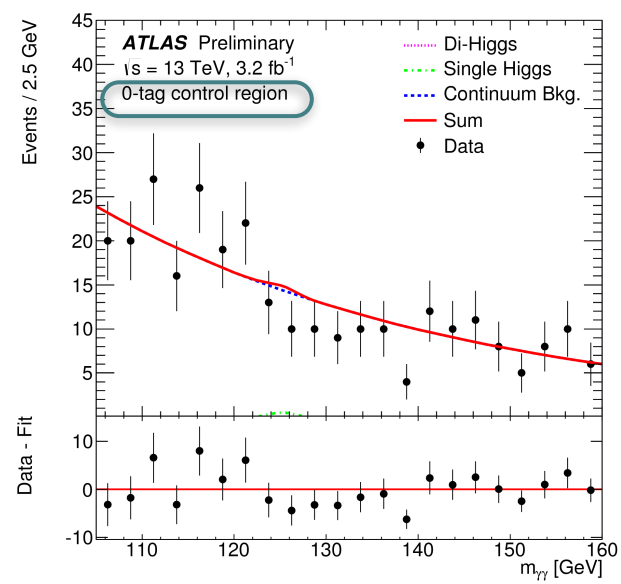
$$N_{SR}^{SM} = N^{SM}\varepsilon_{m_{\gamma\gamma}}^{SM}\varepsilon_{m_{b\bar{b}\gamma\gamma}}^{SM}$$

- N_{SM} sum of the number of single-h and hh events
- ε_{SM} = 0.95 and ε_{SM} is taken directly from simulation



The four-momentum of the bb is scaled by m_H/m_{bb} → improves the $m_{bb\gamma\gamma}$ resolution by 60%

Process	0-tag	2-tag
Continuum background	35.8 ± 2.1	1.63 ± 0.30
SM single-Higgs	1.8 ± 1.5	0.14 ± 0.05
SM di-Higgs	<0.001	0.027 ± 0.006
Observed	27	0



- Resonances > 400 GeV: bbbb and $bb\tau^{+}\tau^{-}$ have better sensitivity due to the higher branching fractions of the SM Higgs boson decays to bb and ττ (6.3%) wrt γγ (0.23%)
- This search focuses on resonances with masses in the range 275 < m_X < 400 GeV, as well as on non-resonant production with similar kinematic properties to the SM Higgs-pair (di-Higgs) production but with an enhanced rate with respect to the SM one